Considering Landowner Participation in Wind Farm Layout Optimization

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Current wind farm layout optimization research assumes a continuous piece of land is readily available and focuses on advancing optimization methods. In reality, projects rely on landowners' permission for success. When a viable site is identified, local residents are approached for permission to build turbines on their land, typically in exchange for monetary compensation. Landowners play a crucial role in the development process, and some land parcels are more important to the success of project than others. This paper relaxes the assumption that a continuous piece of land is available, developing a novel approach that includes a model of landowner participation rates. A genetic algorithm (GA) is adopted to solve the nonlinear constrained optimization problem, minimizing cost and maximizing power output. The optimization results show that, given a projected participation rate, we can identify the most crucial plots prior to the negotiation process with landowners. This will ultimately increase the efficiency of wind farm development. [DOI: 10.1115/1.4006999]

1 Introduction

Developers must consider many wind farm siting factors such as wind resource, topography, surface roughness, road access, transmission lines, tower foundations, and equipment—many of which will be estimates until a costly full site survey is conducted, which requires permission to access the land [1]. When the land is held by individual landowners, as opposed to federal land or offshore, each landowner makes a participation decision that impacts project success, but they must make this decision without exact knowledge about the positioning, appearance, and noise of the turbines. There are many accounts of projects being put on hold or terminated because of landowner issues, see Refs. [2–6]. It is an emotionally and financially complex decision for landowners [7,8].

Similarly, turbine layout is technically complex for developers, and has received attention in the optimization literature. Most research papers use a genetic algorithm (GA) with discrete solution space [7–10] to determine turbine layout, while others have suggested heuristic approaches, such as Particle Swarm Optimization [11], Simulated Annealing [12], Greedy Heuristic [13], and Monte Carlo Simulation [14]. DuPont and Cagan [15], and Chowdhury et al. [16], investigate a continuous solution space. In the interest of brevity, the literature review is incorporated into Sec. 2, which describes the problem formulation. [7–16] assume land availability as a given parameter. In reality, land availability is not determined until negotiations with landowners have concluded. In this paper, we incorporate landowner participation as a string variable in a wind farm layout optimization, and use a GA to solve the associated nonlinear constrained problem. We demonstrate that even with basic data, it is possible to determine which land plots are most important to the success of the project, and that the assumption of continuous land is not necessary to maximize layout efficiency.

2 Problem Formulation

The problem is formulated from the perspective of an experienced development company that can estimate from experience the approximate landowner participation rate, and is formulated to answer the question: "If only P% of landowners agree to participate, which landowners own the plots that are the most crucial to the project?" The demonstration considers nine landowners who each own a 1.52 square kilometer plot, as shown in Fig. 1.

The size of each plot is reasonable, as the average farm size in Iowa is 1.34 square kilometers [17]. Each landowner (marked by a bold number in Fig. 1) owns a square area of land with 16 cells. Turbines can only be placed in the center of each cell—a common discrete optimization approach [7–13].

2.1 Explanation of Model Parameters and Assumptions. In order to simplify the case study, we assume:

(1) All turbines have a 77 m rotor diameter and 80 m hub height, a reasonable assumption for modern turbines [18,19].
(2) Four rotor diameters (4D) separate any two turbines to reduce wake interactions, as assumed in [13,20].
(3) Two wind scenarios:
  (a) Unidirectional uniform wind, 12 m/s from the west.
  (b) Nonuniform wind with variable direction, as shown in Fig. 2 and used in [7,8,12,15]. Note that different representations of wind scenarios are available in [21–25].
(4) The land is flat with a surface roughness of 0.25 mm, within the range associated with sandy soil [26].

2.2 Optimization Model. The objective function minimizes cost while maximizing the total power production, as in [7,8,14,15]. The objective function, Cost of Energy (COE), is defined as

Minimize:

$$\mathrm{COE}(X)=\frac{\mathrm{Cost}(X)}{P_{\mathrm{tot}}(X)}=\frac{N(X)\left(\frac{2}{3}+\frac{1}{3}e^{-0.00174N(X)^2}\right)}{\sum_{i=1}^{N(X)}P_i(X)} \quad (1)$$

Subject to:

$$h_c(X)=\phi(X,c)=0 \quad \forall c\in\{1,\ldots,144\} \quad (2)$$

$$h_{145}(X)=L(X)-n_{\mathrm{yes}}=0 \quad n_{\mathrm{yes}}=4,5,\ or,\ 6 \quad (3)$$

where X is the 153-bit binary string design variable, which represents the availability of the landowners' individual plots of land (based on participation decisions) and the turbine locations, as shown in Fig. 3.

X_k represents the k^{th} bit of X; c is the cell label.

$$\begin{aligned}&\text{For } 1\le k\le 9\\ &X_k=0 \quad \text{IFF landowner } k \text{ says no}\\ &X_k=1 \quad \text{IFF landowner } k \text{ says yes}\end{aligned} \quad (4)$$

$$\begin{aligned}&\text{For } 10\le k\le 153,\ c=k-9\\ &X_k=0 \quad \text{IFF cell marked } c \text{ does not contain a turbine}\\ &X_k=1 \quad \text{IFF cell marked } c \text{ contains a turbine}\end{aligned} \quad (5)$$

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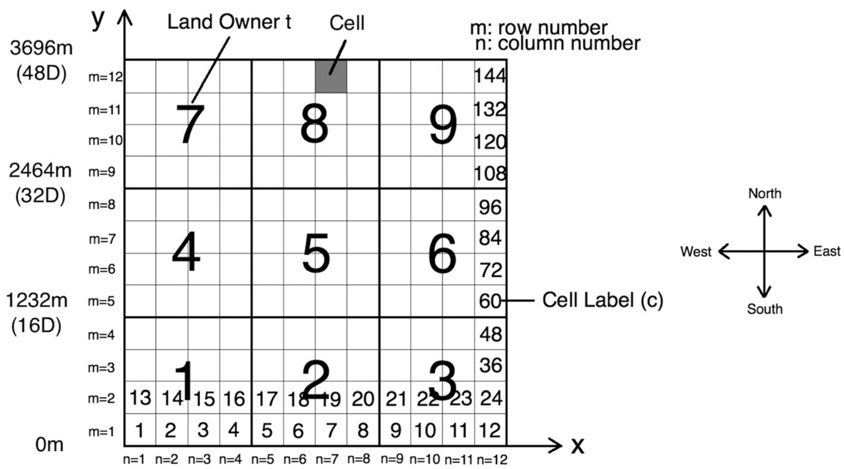

Fig. 1 Problem representation

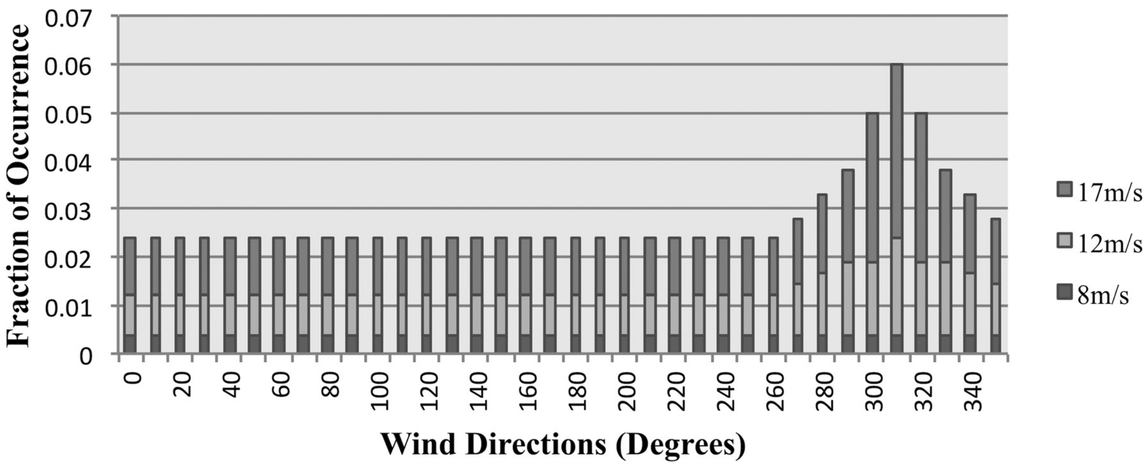

Fig. 2 Wind distribution for multidirectional nonuniform wind scenario [7,8,12,15]

$$X = \underbrace{101111010}_{\text{Landowners' decisions (9 bits)}}\ \underbrace{0101011010\ldots\ \ldots\ \ldots10111000}_{\text{Turbine locations (144 bits)}}$$

Fig. 3 Binary string representation of *X*

In Eq. (1), the estimated farm cost per year is based solely on the number of turbines, $N(X)$. $P_{\mathrm{tot}}(X)$ is the farm's power production in kilowatts, and $P_i(X)$ is represented by a power curve as in [8,15,25]. The wind speed $u_i(X)$ for turbine i is a function of X, discussed in Sec. 2.3.

$$\mathrm{Cost}(X) = N(X)\left(\frac{2}{3}+\frac{1}{3}e^{-0.00174N(X)^2}\right) \tag{6}$$

$$P_{\mathrm{tot}}(X) = \sum_{i=1}^{N(X)} P_i(X) \tag{7}$$

$$P_i(X) = 0.3u_i^3(X) \tag{8}$$

In Eqs. (2) and (3), $h_c(X)$ and $h_{145}(X)$ are equality constraints. $L(X)$ is a function of X that calculates the number of participating landowners in the problem solution to match this to the parameter that specifies this, n_{yes}.

$$L(X) = \sum_{k=1}^{9} X_k \tag{9}$$

$\phi(X,c)$ constrains X for a cell c such that a turbine can only be placed in the land of a participating landowner. When a turbine is located in the land of a nonparticipating owner, $\phi(X,c)=1$; otherwise, $\phi(X,c)=0$. For the cell marked c (refer to Fig. 1), the row number (m) and the column number (n) of cell c can be calculated by

$$m\left\lfloor\frac{c-1}{12}\right\rfloor+1 \tag{10}$$

$$n = c-(m-1)\times 12 \tag{11}$$

where $\left\lfloor\frac{c-1}{12}\right\rfloor$ refers to the nearest integer less than $\frac{c-1}{12}$. Therefore, the coordinates of a potential turbine in cell c are

$$(x,y) = (2D+(n-1)\times 4D, 2D+(m-1)\times 4D) \tag{12}$$

The landowner who owns cell c can be found by

$$t = \left\lfloor\frac{n-1}{4}\right\rfloor + 1 + \left\lfloor\frac{m-1}{4}\right\rfloor \times 3 \tag{13}$$

where t is the landowner label as shown in Fig. 1. Therefore, $\phi(X,c)$ can be defined as:

$$\phi(X,c) = \begin{matrix} 1-X_t & \text{when } X_{c+9}=1 \\ 0 & \text{when } X_{c+9}=0 \end{matrix} \tag{14}$$

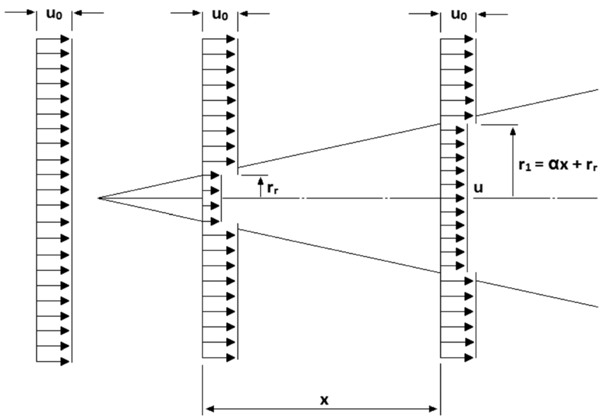

Fig. 4 Wake loss model [7,8,15,31]

2.3 Wake Loss Model. The effects of an upstream turbine's wake on the energy output of downstream turbines can be modeled using different approaches, see Refs. [25,27,28]. The accuracy of the different approaches has been found to be similar [29,30], so we selected the widely used Jensen model [7,8,15,31,32], represented in Fig. 4 with wind blowing from left to right and ambient wind speed u_0.

After establishing a momentum balance and assuming that "the wind speed directly behind the rotor is approximately one-third of the oncoming wind speed" [15,32], Eq. (15) is obtained to calculate the downstream wind speed u of a turbine influenced by the wake of one upstream turbine

$$u = u_0\left(1 - \frac{2}{3}\left(\frac{r_r}{r_1}\right)^2\right) \tag{15}$$

where r_r stands for the rotor radius, r_1 refers to the effective downstream wake radius, and u is the downstream wind speed in the wake of an upstream turbine at distance x [15]. To solve for u, Jensen's model assumes that r_1 and x follow a linear relationship as shown by the triangular wake in Fig. 4 and Eqs. (16) and (17) [15,32], in which z is hub height, z_0 is the surface roughness, and α is the entrainment constraint.

$$r_1 = r_r + \alpha x \tag{16}$$

$$\alpha = \frac{0.5}{\ln(z/z_0)} \tag{17}$$

In the case of multiple wakes from n upstream turbines, the kinetic energy deficit of multiple wakes is assumed to be equal to the sum of the energy deficits [7,15]. The resulting effective downstream wind speed can be calculated by [8,15]

$$\bar{u} = u_0\left[1 - \sqrt{\sum_{i=1}^{n}\left(1 - \frac{u_i}{u_0}\right)^2}\right] \tag{18}$$

Table 1 Unidirectional uniform wind and multidirectional nonuniform wind

Results	Case (a)	Case (b)	Case (c)
Unidirectional uniform wind			
Landowner participation	4	5	6
COE	0.001740	0.001671	0.001599
Total power (megawatt)	8.09	9.97	11.84
Number of turbines	16	20	24
Multidirectional nonuniform wind			
Landowner participation	4	5	6
COE	0.000851	0.000831	0.000824
Total power (megawatt)	30.31	32.40	33.34
Number of turbines	37	39	40

3 Solution and Results

3.1 Method and Implementation. A GA is a probabilistic search algorithm that employs the mechanics of natural selection and survival of the fittest individuals [8]. Unlike traditional numerical optimization methods, GAs do not need derivative information and are less likely to get trapped in local optimum [33,34]. Our case study is a nonlinear complex problem with 153 binary variables. The objective function is nonderivative and multimodal

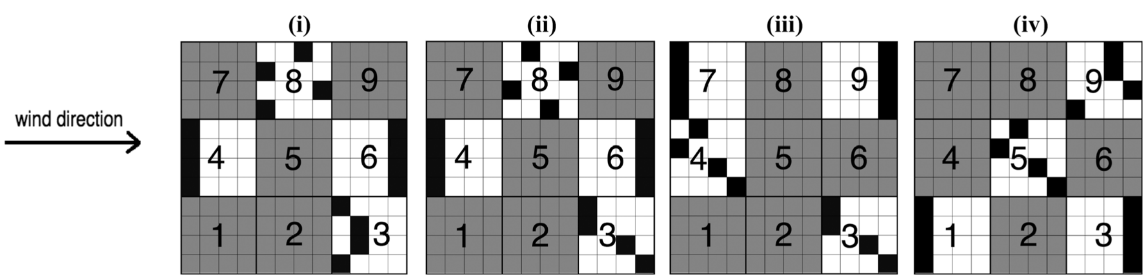

Fig. 5 Unidirectional uniform wind case (*a*) example optimal layouts

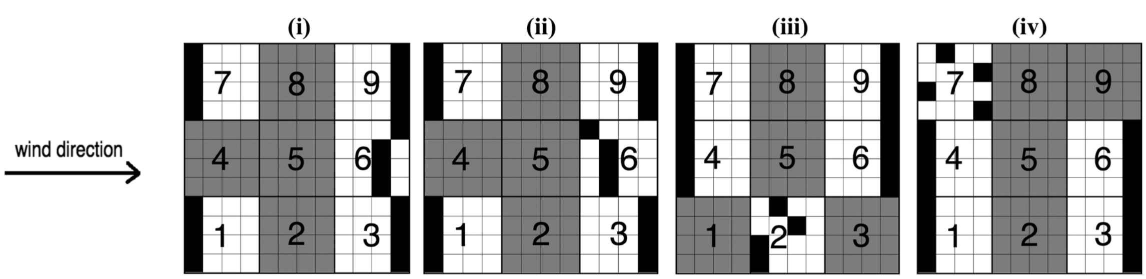

Fig. 6 Unidirectional uniform wind case (*b*) example optimal layouts

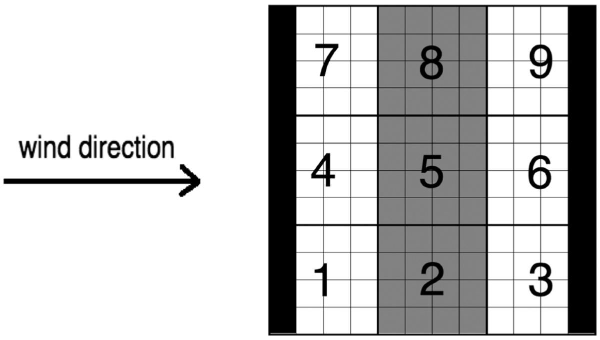

Fig. 7 Unidirectional uniform wind case (*c*): unique optimal layout

(it is possible to have more than one optimal layout). A GA is a suitable approach for this problem, as it can easily deal with binary variables.

The fitness function is composed of two parts: the original objective function—COE(X) (Eq. (1)), and a penalty function $\varphi(X)$ for constraints (Eqs. (2) and (3)) [35,36]

$$\text{Fitness} = \text{COE}(X) + q \cdot \varphi(X) \tag{19}$$

where q is a multiplier that determines the magnitude of the penalty [35]. The penalty function is defined as

$$\begin{aligned}\varphi(X) &= \sum_{c=1}^{144} [h_c(X)]^2 + [h_{145}(X)]^2 \\ &= \sum_{c=1}^{144} [\varphi(X,c)]^2 + [L(X) - n_{\text{yes}}]^2\end{aligned} \tag{20}$$

Three cases are considered in this study: (a) 4 out of 9 landowners agree to participate (44%); (b) 5 out of 9 landowners agree to participate (56%); and (c) 6 out of 9 landowners agree to participate (67%). Each case takes into account two wind scenarios as mentioned in assumption 3 of Sec. 2.1.

3.2 Optimization Results. Matlab's GA solver from the Optimization Toolbox is adopted to solve this problem. A population of 1000 individuals was allowed to evolve over 1000 generations. As GA is not guaranteed to converge on the same results over multiple runs, the optimization program for each case study was allowed to run over ten times. The results of the optimization are recorded in Table 1

Figures 5–8 represent optimal layouts of unidirectional uniform and multidirectional nonuniform wind cases. The least crucial plots of land are represented by the grey squares, and the optimized turbine locations are represented by the black squares.

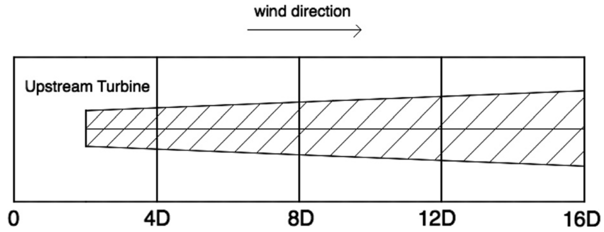

Fig. 9 Wake loss region for 4 cells

3.3 Results Analysis. For unidirectional uniform cases (a) and (b), the optimal layouts are not unique, some of which are shown in Figs. 5 and 6. There is no one (or more) most crucial land plot; different combinations of land plots will result in equally optimal COE. Some patterns can be found by comparing optimal layouts. For example, for the land plots that do not have upstream or downstream turbines, such as plots 3 and 8 in Fig. 5 (i), the optimal locations of turbines are not unique as shown in Fig. 5 (i) compared with Fig. 5 (ii). The turbines can be placed anywhere in plots 3 and 8 as long as there is only one turbine in a row. Figure 9 shows the explanation for this: assuming the upstream turbine is located in the leftmost cell, the wake loss region is represented by the shaded area. Figure 9 indicates that, for a single plot of land in the unidirectional uniform wind cases, the upstream turbine will only cause wake loss for a turbine placed in the same row. Therefore, for the land plots that do not have upstream or downstream turbines, turbines can be placed anywhere as long as there is only one turbine in a row.

Unidirectional uniform case (c), in which 6 landowners participate, has a unique optimal layout shown in Fig. 7. This layout makes full use of the solution space to separate downstream turbines from the ones upstream. We also ran the optimization for higher rates of participation and found that the optimal results are the same as case (c) when more than six landowners agree to participate.

Each multidirectional nonuniform wind case has a unique optimal layout (Fig. 8). The optimal number of turbines in each case is larger than that for the uniform cases because of the high wind speed of 17 m/s as opposed to 12 m/s. The inclusion of more turbines indicates that when wind speed is high, the effective downstream wind is favorable even with wake loss, and turbines can be placed closer together. Land plots 1 and 9 are included in all three optimal results, as there are no upstream or downstream plots in the prevailing wind direction (310 deg), identifying these plots most crucial to the success of the farm.

4 Discussion and Conclusion

The results in Sec. 3.2 suggest:

(1) Increased landowner participation does not always decrease cost of energy, as found in the uniform unidirectional results for six landowners participating and up, which do

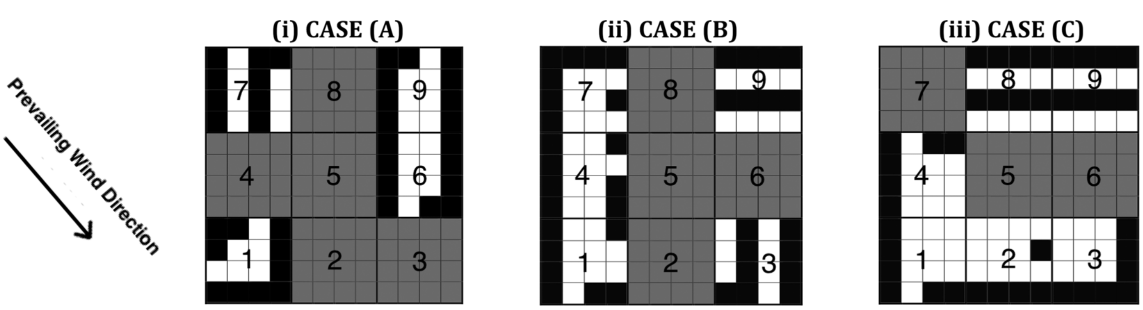

Fig. 8 Multidirectional nonuniform cases (*a*),(*b*), and (*c*) unique optimal layout

not have any turbines on plots 2, 5, and 8. Using this information, developers can save time and money avoiding unnecessary land negotiations.

(2) There may be some land plots that are more crucial to the success of the project than others, such as plot 1 in the multidirectional nonuniform cases. Using this information, developers can expend more effort and money on negotiating for the most crucial plots of land.

(3) There may be equally optimal layouts that involve the participation of different sets of landowners, as in unidirectional uniform cases (a) and (b). Using this information, developers can avoid difficult negotiations with a particular landowner and target an alternate layout, saving time, money, and potential failure of the entire project.

One reason that developers currently approach all landowners with equal compensation packages is that no one realizes the importance of their land to the project, thus making negotiations easier. Companies typically use a standardized approach for acquiring landowners, such as first sending out an invitation postcard and then host a public dinner and presentation, for an example see Ref. [37]. This approach can be improved. One idea is to tailor the negotiation approach to the decision-styles of landowners with crucial plots while still offering an equal monetary benefit package to all. Future work will create a decision model for landowners and use it to investigate negotiation and compensation impacts on the optimal layout. Some plots that are not used for optimal energy production may be needed for electrical grid access and roads. Developers may be able to guarantee to these landowners that no turbines will be placed on their land, thus shortening negotiations and reducing compensation. An area for future work is to include road, grid, and zoning information, thus making it possible to address such issues.

Using our approach, a developer can save considerable money and time that might be otherwise spent on securing noncrucial land plots. Because our demonstration is on a small scale, the savings could actually be orders of magnitude larger when the project involves more landowners—some projects involve more than 100 landowners, for example see Ref. [38]. Compensation paid to individual landowners ranges from \$4000 to \$8000 annually per megawatt [39–41]. In multidirectional case (a), ten turbines producing approximately eight megawatts were placed on plot 1, resulting in an estimated compensation for the landowner between \$32,000 and \$64,000 annually, so the cost savings may be dramatic over a twenty-five year lifespan of a farm.

The problem formulation is by no means comprehensive. The case study uses a cost model based solely on the number of turbines and will be improved to account for landowner recruitment costs and other factors. In reality, not all landowners will have equal size plots with even terrain. It is important to study nonidentical land areas and investigate the trade-off in importance of factors such as size, shape, and location of the land areas. There are also zoning issues to model; for example, states have laws about how close a wind turbine can be placed to buildings and roads. Finally, the accuracy of predicting land availability, wind conditions, and even turbine efficiency changes throughout the course of developing the farm, so uncertainty in parameters should be accounted for in early-stage layout optimizations.

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