Grid-aware Green Datacenter Placement

Xiaoying Wang
Department of Computer Technology and Applications,Qinghai University, Xining, Qinghai, 810016, China
Email: wxy_cta@qhu.edu.cn

Md E. Haque, Íñigo Goiri, Ricardo Bianchini, Thu D. Nguyen
Department of Computer Science
Rutgers University, Piscataway, NJ 08854-8019, USA
Email: {mdhaque, goiri, ricardob, tdnguyen}@cs.rutgers.edu

Divya Kurthakoti Chandrashekhara
Siemens Corporate Research
Princeton, NJ 08540, USA
Email: div.s.sya@gmail.com

***Abstract*—Due to the growing concern for huge energy consumption, Internet serivce providers tend to build data centers with renewable energy support to reduce cost and the carbon footprint. Prior work about "green" data center placement issues didn't consider the potential impact on the elecitricy grid by penetrating large loads and intermittent power generations from renewable resources. In this paper, we propose a holistic framework which incorporates together the cost of data centers, renewable energy power plants and the utility grid. By considering various factors such as land, building, hardware costs as well as the losses on the grid network, we try to solve an optimization problem to minimize the overall cost for both service providers and utility grid operators. Our results show that transmission losses and distribution losses of the regional grid would have remarkable effect on the decision of selecting locations for data centers and renewable energy power plants. Furthermore, co-location choices for distribution load generation sources and loads as data centers are not always better, even comparing only the losses on the grid, which is quite not intuitive. Our work gives a way to seek for optimal locations in the capacity planning stage and also shows the importance for cloud service companies and grid operators to collaborate for reduction of overall cost.**

I. Introduction

As reported recently, the energy consumption of data centers keeps growing while more and more enterprises and organizations are building their own data centers [1], [2]. The increasing speed of the data center energy consumption is approximately 10-12% per year recently [3]. The carbon emission and environment pollution issues attract insights of seeking for clean energy resources. Many IT companies such as Google [4], Apple [5], and McGrawHill [6] are trying to build their data centers together with renewable energy power plants.

Usually, generation of sustainable energy like solar and wind will be closely related to the weather condition at certain locations. As far as we know, there might be different choices for building the data center and the power plants. Both on-site and off-site generation are possible approaches [7]. By grid-centric approaches, the renewable energy will be generated at locations with sufficient renewable sources and pumped into the grid. On the other hand, co-location and self-generation approaches sit the data center and the power plant at the same location to facilitate management and avoid long-distance losses. Since it seems no approach is perfect, we argue that companies essientially expect benefits from the investments by building up data centers and green power plants. However, since the renewable energy generation is mostly intermittent and sometimes might bring great peneration current into the eletricity grid, the capacity should be carefully planned and will be limited from the perspective of grid operators. For them the stalability of the grid is the most import thing, and some tiny failures may make an area of grid system completely out of power [8].

Since data centers are becoming quite large loads for the electricity grid, they are supposed to have a significant impact on the operation of power grid [9]. Large data center loads might increase the grid load and lead to regional failures of the electricity system. Especially the emergence of the renewable energy sources with intermiitent nature increases the demand for more reliable electricity networks. Furthermore, grid losses are on of the largest expensis for the power system operators [10]. EIA (U.S. Energy Information Administration) [11] has estimated that the electricity transmission and distributaion losses all over the U.S. is about 6% of the electricity that is transmitted and distributed each year (averaged from 1990 to 2012). Thus, reduction of these losses for the grid can greatly affect the total operational costs.

In this case, companies who want to build data centers with either on-site or off-site renewable energy plants have to get the permission from the grid operators first in order to reduce the unexpected influence to the grid operation. Since the grid losses will also finally turn into expenses for end-users, service providers may want to collaborate with grid operators to minimize the overall cost when planning locations and capacity for the data centers. In the current literature, data center placement issues have been mentioned in some prior work [12]–[15], and there are also some research focused on the capacity planning of green data centers [16], [17]. Nevertheless, these work hasn't considered the impact of data center placement on the grid itself, which might also lead to comparable costs as other costs for data centers.

In this paper, we attempt to set up a different point of view, by combining the consideration for cloud service providers and energy companies together and aiming at the minimizationo of the overall cost for both. First, we investigate the impact of data center placement and its importance to the grid by studying a region of grid network. We pay special attention to the data center size, data center locations and the variation of renewable power generations. Second, we formulate the

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optimization framework, which incorporates the costs of data centers, renewable power plants and power grid into one objective. We also try to solve it under necessary constraints by using several different approaches. Then we conduct a case study in the New England area of the United States, by sitting and provisioing data centers and power plants at different locations, with the purpose of minimizing the overall cost. Results show that the transmission and distribution losses have remarkable impact on the decision of selecting best locations for green data centers. Furthermore, the co-location choices by sitting the data center and green plants together don't show advantages despite of the reduced line cost and distribution cost, which is not that intuitive as prior work thought.

Contributions of this paper. The main contributions of this paper includes: (i) it quantifies the potential impact of data center placement on the bus network of power grid, and (ii) it proposes a framework for smart placement of both data centers and renewable energy plants in the power grid network. (iii) it formulates an optimization problem and gives a solution approach to find out good choices for sitting and provisioning data centers when considering grid costs.

To the extent of our knowledge, there is no previous work considering the jointly placement issues of data centers and green power plants while caring about the grid operational costs together. The remainder of the paper is organized as follows. Section II first quantifies the potential of data centers together with wind farms by placing them into different buses of the grid network system. In Section III, we describe the optimization framework in detail, showing the integration of various parameters of the entire problem. Section IV evaluates the costs and illustrates breakdown of the total cost by different kinds of strategies. In Section V, we present some prior work related to this paper. Finally, the conclusion is given in Section VI.

II. Quantifying the Impact of Data Center Placement on Power Grid

Before studying the issues of data center placement in smart grid, it is crucial to look at and quantify the impact of different placement choices. In this section, we attempt to simulate the effects of putting data centers into the power grid with/without wind farms, and see how it will affect the grid in terms of transimission losses and stability.

To quantify and compare the effects of different cases, we use following three metrics:

- *Transimission Losses*. When electricity is transmitted from generator to distribution network areas, some amount will be lost during the transimission. In general, losses can be estimated from the difference between produced power and the consumed power, assuming no theft of utility. Reducing the losses is important for the power grid to avoid energy waste, which could be affected by the power flow of the grid system.
- *Line capacity violation*. For a transimission line (referred as branch hereafter in the paper) in the grid system, the amount of power can be sent through it will be limited, depending on the length of the branch. If the power injected into the branch exceeds the limit, wires might be melt under high temperature, which leads to unpredictable dangerous situations. Thus, it's crucial to keep the line limit unviolated in order to keep the grid safe and reliable.
- *Voltage violation*. Voltage stability is very important for the performance of the grid system. Normally a voltage magnitude of 1.0 p.u. is considered to be favorable [18]. For load buses, a range of 0.95-1.05 p.u. could be considered acceptable. If the bus voltage goes out of the range, we regard the system as voltage unstable. XW: This can hardly be observed, and didn't occur in the following experiments.

A. Setup

To quantify the effect of placing datacentes into different locations of the power grid system, we study a situation where a transimission system has five wind farm installation and several large-scale data centers connected to the buses.

1) Transimission network: In our experiments, we consider the transimission network based on the New England 39-bus network, as shown in Figure 1.XW: should we re-draw this figure by ourselves?? This is a well-known bus system [19] as which consists of 10 generators, 19 loads and 46 lines and transforms. The 10 generator buses are numbered from 30-39 in Figure 1, where bus 31 is a slack bus. Specifically, bus 39 represents the aggregation of a large number of generators interconnected to rest of US/Canada.

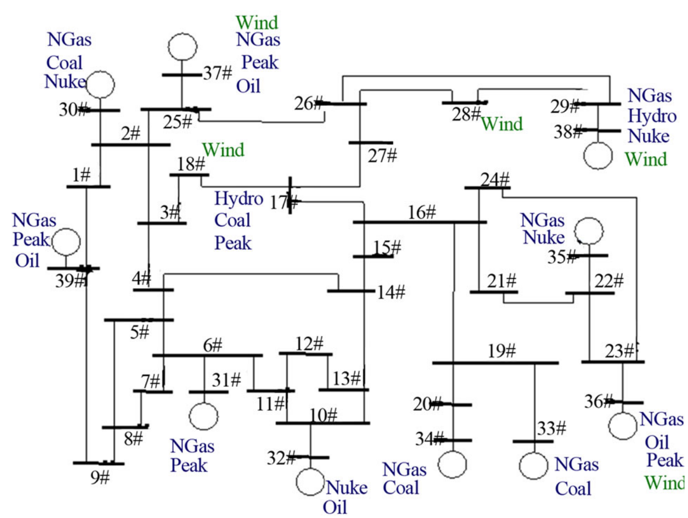


Fig. 1: New England 39 bus network

During our simulation experiments, we compute the power flow for two kinds of system loads: *nominal* and *peak*, corresponding to the normal load and the highest load throughout a whole year respectively. Note that the network constraints will become tight when facing peak load, where violations are more common to occur.

2) Data center model: Besides the grid system load, we also put the loads of data centers into the grid network, based on the geographical mapping according to [20]. We use six datacenters representing six states in New England, and the size setting of them is listed in Table I. Note that here each data center represents the total load of data centers in the whole state. In order to estimate the size of an "aggregated" data center in a certain state, the follow equation is used:

$$L_i = \frac{n_i * 9.8GW}{1278} \tag{1}$$

where L_i is the aggregated load of the ith state, n_i is the number of datacenters reported in that state, 9.8GW is the upper bound of total electricity used by US data centers in 2010, according to the report [2], and 1278 is the number of datacenters in US collected and reported in [20]. However, according to [2], for the summarized load of data centers, there is an increase of 56% from 2005-2010. Hence, we are assuming the increasing percentage from 2010-2014 is 56%*0.8=45%, and after adjustment we are using $L_i' = 1.45L_i$ as the data center load for the target grid system. Besides, the data centers are mapped to different buses according to their geographical locations, which can also be found in Table I.

TABLE I: Background data center load and location settings

DC No.	State	Number of DCs	Estimated size(MW)	Mapped Bus No.
DC1	Connecticut	12	133.43	6
DC2	Maine	3	33.36	29
DC3	Vermont	4	44.48	25
DC4	Rhode Island	3	33.36	20
DC5	New Hampshire	4	44.48	16
DC6	Massachusetts	27	300.21	4

3) Renewable energy: To model renewable energy power installation, we use data collected from five wind farms located in New England area. XW: (Where is the data derived from?) As Figure 1 shows, they are connected to bus 18, 28, 36, 37 and 38 respectively. The locations and capacity settings of the 5 wind farms can be found in Table II. As we know, the amount of wind power generation is mainly determined by the wind speed. For a GE 1.5MW wind turbine [21], the cut-in speed is between 4-5m/s, and the cut-off speed is 25m/s. The power generation approaches the rated capacity when the wind speed rises up to around 13m/s. In the follow experiments, we classify the wind speeds into four categories: ZERO (0-3m/s), LOW (4-6m/s), MEDIUM (7-11m/s), and HIGH (>11m/s).

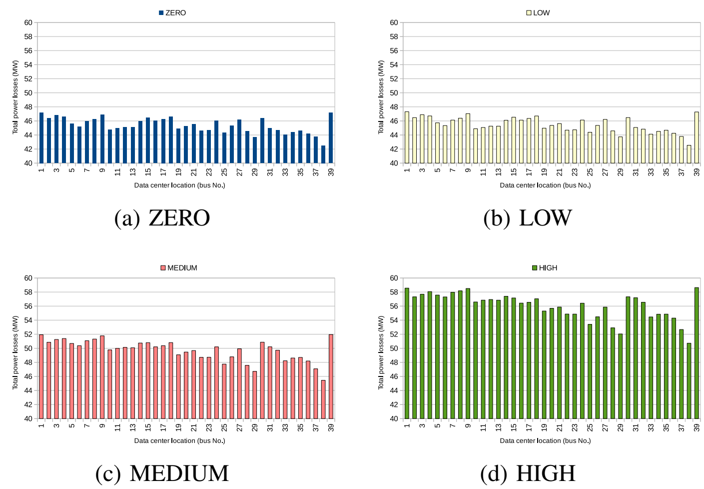
TABLE II: Wind farm settings

WF No.	Bus No.	State	Capacity(MW)
WF1	18	?	100
WF2	28	?	90
WF3	36	Vermont	90
WF4	37	Maine	90
WF5	38	Massachusetts(?)	90

B. Case study

Based on the settings described above, we conduct simulation experiments to study the impact of data center placement at different locations on the performance and stability of the tested grid network. Furthermore, we also investigate the potential impact of data center capacity on the grid, and try to examine the effect of jointly placing a large-scale data center and a wind farm.

1) Impact of data center location: First, we attempt to conduct the study of the impact of connecting a new data center to different buses. Based on the basic configuration of the grid system with nominal load, including the existing 6 data centers and 5 wind farms, we try to establish a new data center with the size of 100MW and put it into the grid network. Figure 2 shows the comparison of total system losses when the extra data center locate on each bus from 1-39, under the condition of four different wind speed settings.



(a) ZERO (b) LOW

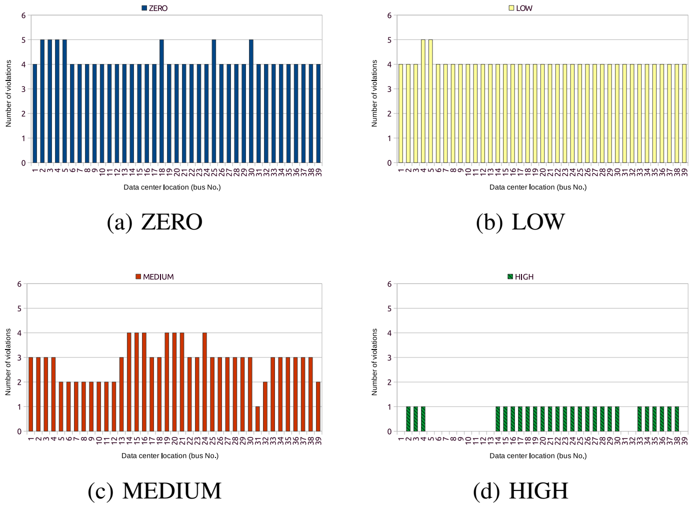
(c) MEDIUM (d) HIGH

Fig. 2: Impact of data center locations on losses

As shown, the total system losses vary a lot when putting a new datacenter in different places. For example, when the wind speed setting is MEDIUM, the maximum loss (at bus 39) could be 14% larger than the minimum value (at bus 38), and the standard deviation is 1.48. This highlights that choosing the place for a large-scale data center might greatly affect the power grid and provide the potential for helping the grid manager to save energy losses.

Note that in the previous experiment there are no violations occuring, since the system load is far below the constraints. Next, we change the scenario to peak system load and conduct the simulation again in order to investigate the impact of data center placement on line capacity violations. Evaluation results are illustrated in Figure 3, which highlights that the number of violated branches is quite different when the data center is connected to different buses. In particular, take Figure 3c for example, there is only one branch violated when the data center is connected to bus 31, but 4 branches violated when it's connected to bus 14.

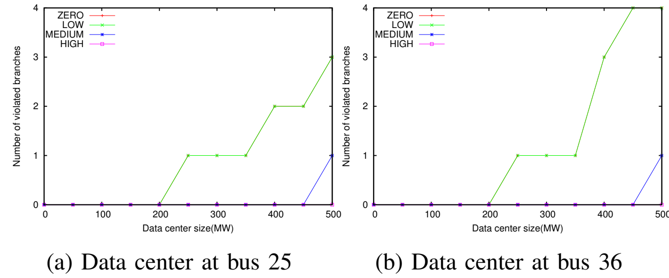
2) Impact of data center size: Here, we set the wind speed of the five wind farms all to ZERO, LOW, MEDIUM and HIGH repectively and see how the data center size will affect the total power losses of the grid system. The added data center will be fixed on a certain bus location, and only the load of the data center varies. Figure 4 shows the results under four scenarios corresponding to different wind speeds, when the data center is located at bus 1, 2, 18, 25, 31, 36, 38 and



(a) ZERO (b) LOW

(c) MEDIUM (d) HIGH

Fig. 3: Impact of data center locations on violations



(a) Data center at bus 25 (b) Data center at bus 36

Fig. 5: Impact of data center sizes on line capacity violations

39 respectively. Note that the eight buses were chosen out of 39 buses since they are representive for all kinds of variation types.

From Figure 4a, we can see that the change of the data center load will affect the system performance obviously, with the total power losses varying from 44.9 MW to 64.2 MW. A more important finding is that, with the presence of wind farms, increasing the data center load would have different impact on the system losses when placed at different locations. For example, in Figure 4b and Figure 4c, it can be observed that, the losses increase as the load of the data center become heavier when the data center is placed at bus 1, 2, 18 and 39. However, when the data center is connected to bus 25, 36 or 38, there is a certain size for the data center to make the system losses achieving a minimal value. Since the load of the data center could be adjusted by a variety of techniques [], this implicates the possibility that it could be leveraged to confront the variability of the wind power generation, which could have negative effect to the grid network. It's also notable that no matter how large is the data center size, the losses keep constant if the data center is connected to bus 31. This is because bus 31 is a slack bus, which is used to balance the active and reactive power in the grid system by taking up any power mismatch between load and generation.

Furthremore, we also investigated the impact on the grid branches by changing the size of the data center. Figure 5 shows the results when the data center with varying sizes is connected to bus 25 and 36 repectively. Results of other bus locations show similar characteristics and thus will be omitted here. It seems that the possibility of getting branches violated will become larger when the data center's load goes higher. On the other hand, it's notable that high wind speeds lead to fewer violations, which implicates that with wind power generation, the grid can tolerant higher load from data centers.

3) Comparison before and after placing the data center and wind farm: In order to investigate the impact of placing data center and wind farm into the grid network, we compare the losses of eight different cases, including BASE (the base grid network), DC (base grid with one 100MW data center), LOW_WF, MED_WF, HIGH_WF (base grid with one extra wind farm set to LOW, MEDIUM, HIGH wind speed respectively), DC&LOW_WF, DC&MED_WF, DC&HIGH_WF (based grid with both data center and wind farm corresponding to different wind speed settings). The comparison results are illustrated in Figure 6. It implies that placing a data center at a proper location might help the grid with/without wind farms to reduce total power losses.

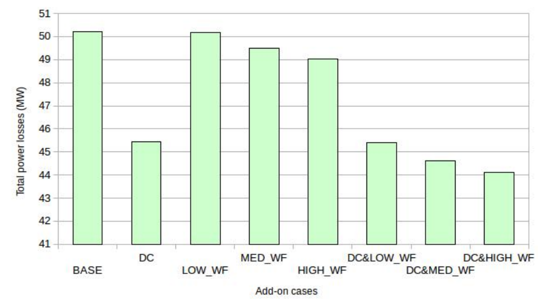


Fig. 6: Losses before and after data center and wind farm placement

4) Jointly considering the placement of data center and wind farm: Assuming that a new data center and a new wind farm will be established and connected into the power grid system, where is the best place for them to be constructed in order to bring least negative impact to the grid network? We try to examine the different effect of the following four stategies:

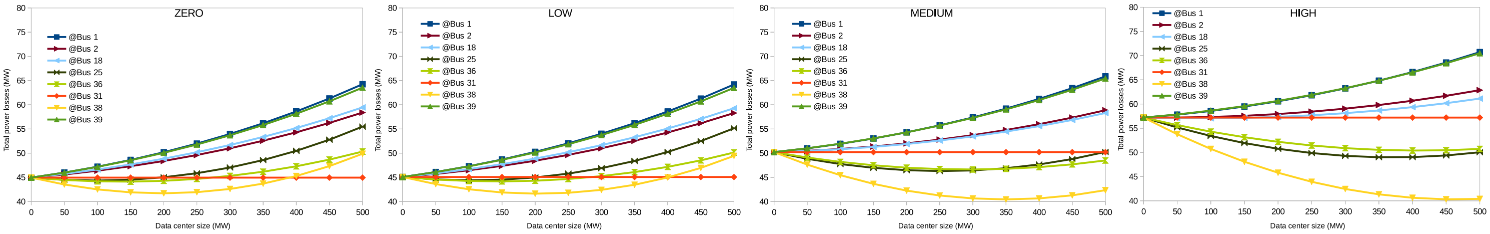
(1) *Only DC*: We only consider the placement of the data center to minimize the power losses of the whole system, without the knowledge of wind farms.

(2) *Only WF*: We only consider the placement of the wind farm to minimize the impact, without knowing about the data center.

(3) *Co-location*: We put the data center and the wind farm together and connect both of them to the same bus.

(4) *Jointly*: We jointly consider their impact together by comparing the situation when they are connected to different buses and try to find the best one of the combinations.

When the wind speed and the size of the data center are set to different values, the minimal losses could be different. We



(a) Wind speed set to ZERO (b) Wind speed set to LOW (c) Wind speed set to MEDIUM (d) Wind speed set to HIGH

Fig. 4: Impact of data center sizes on losses.

use the four strategy to find the place with minimum losses of the whole system, and the results are illustrated as in Figure 7. A main observation is that co-location is not a best choice in terms of reducing total power losses of the entire grid. Minimum losses are usually achieved when the data center and the wind farm are placed into different places.

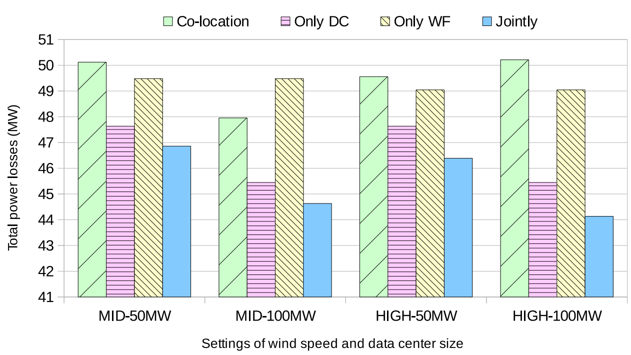


Fig. 7: Comparison of different placement choices

III. Framework for smart placement

The previous section highlights that placing data centers and wind farms has obvious impact on the grid trasmission network system. Thus, when a service provider is looking for best locations to estabish a network of green data centers, the grid operational cost should also be included as one of the most important factors into consideration. Another observation is that co-location of the green data center and the green energy plant seems not always be the best choice. In this case, we try to study how to seek the best locations for both the data center and the green energy plant, which are designed to be connected to the same grid network.

By grid-aware placement, we attempt to efficiently select a set of locations for one or more data centers to support a given amount of computational power, as well as one or more green power plants (e.g. solar, wind or others) to provide a given power capacity. The main goal is to minimize the overall cost for data centers, green power plants and also the grid network operation. The next subsections defines some important parameters in the selection procedure. Then, the cost model and the entire optimization problem will be formulated and described.

A. Parameters for the placement framework

Table III gives all of the parameters defined in our framework. These parameters relate to costs, revenue and losses over different geographical locations. We generally classsify them into three categories: data-center-related, renewable-related and grid-related.

1) Data-center-related costs: Given a target capacity of how large a data center is planned to build, we can calculate the capacital cost first. The capacital cost of a data center at location l, denoted as $DC\_CAPcost(l)$, can be broken down into land cost ($DC\_landCost(l)$), building cost ($DC\_buildingCost(l)$) and hardware cost($DC\_hwCost(l)$). Land cost can be computed by land price at that location and the accommodated data center capacity. Building cost depends on the maximum capacity of the data center, too. Hardware cost contains both server cost and switch cost, which can be computed given the total capapcity of the data center. Besides, hardware cost also includes costs for building lines connecting the data center to the Internet backbone and the trasmission grid, denoted as $costLineNet(l)$ and $costLineGrid(l)$ here respectively. We assume them independent of the data center size, but dependent on the location l of the data center.

Besides capital costs, operating and managing a data center also incurs operational cost, including costs for using the network bandwidth and the electricity from the power grid. We denote them as $DC\_netCost(l)$ and $DC\_energyCost(l)$ repectively, which both depend on the location l of the data center. Furthermore, the energy cost for the data center is also related to the varying demands of the data center workload over different time period, denoted as $demand(l,t)$ hereafter.

2) Renewable-related costs: The costs for building and running a renewable power plant also include capital costs and operation costs. The capital cost of a type r plant at location l, denoted as $RE\_CAPcost(l,r)$, can be broken down into land cost ($RE\_lanCost(l,r)$), building cost ($RE\_buildCost(l,r)$) and line cost ($costLineNet(l)$) for connecting to the transmission grid. Specially, if we are also building a data center in the same location, the connection line to the grid could be shared by the plant, and in this case the line cost could be saved. Similarly, the land cost for renewable power plant depends on the needed area and the land price at that location. The building cost mainly depends on the desired capacity of the plant.

Regarding operational costs, we assume that the human and labor costs for maintence and operation are same over different locations. Thus, by operating the renewable power plant, we only consider the possible renevue it could bring by generating electricity power and transmitting power to the grid. Here, we regard the revenue as a negative cost for the power plant, denoted as $RE\_OPrev(l, r)$, which is closely related to the power generation efficiency at the location and the energy selling price there.

3) Grid-related costs: When connecting the data centers and the renewable energy plants to the utility grid, we are adding both generation and consumption components into the network. This will change the power flow of the whole network, and thus the total losses of the transmission network will be different. Thus, the transmission loss ($transLoss(t)$) will be affected by the generating and consuming power amount of data centers and renewable plants, and also the buses they are connected to, as we showed in Section II.

Besides, distributing power to the end-users on the grid will also incur losses. Here we only consider the additional distribution losses for delivering power to the data centers, denoted as $distLoss(t)$. Then the grid costs include both transimission losses and distribtion losses in our framework.

On the otherhand, during the transimission process the line capacity might be violated if the power flow exceeds the limit. We use $numLineVio(t)$ and $numVolVio(t)$ to denote the number of line capacity violations and voltage violations during the power transmission and distribtion procedure. The grid operator will try to avoid such violations when operating the power grid system.

B. *Optimization problem formulation*

Using the parameters shown in Table III, we can formulate the optimization problem as shown in Figure 8. The problem is set up from the perpective of both IT company and the grid operator, who want to collaborate for building up green datacenters, with the purpose of minizing the summarized cost including data center cost, green power plant cost and the grid cost.

Denote $\mathcal{L}$ as the set of all candidate locations, $\mathcal{T}$ as the set of all time epochs, $\mathcal{R}$ as the set of all types of renewable energy. The input of the optimization problem is listed as follows: (1) the total computational capacity of all the data centers to set up, denoted as $CapacityDC$; (2) the parameters of each location in $\mathcal{L}$ during each time epoch in $\mathcal{T}$ such as prices, PUE (Power Utilization Efficieny), demand, power generation efficiency and so on; (3) the minimum availablility constraint for the data center network. (XW: to limit the number of data centers) The ouputs of the problem is the lowest cost found and the corresponding locations for data centers and renewable power plant, as well as the capacity provisioned at each location for data centers or green power plants (if any).

Equation 1 in Fig.8 shows the optimization objective of our defined problem, i.e. $TotalCost$, where $DC(l)$ and $RE(l, r)$ are booleans indicating whether to place a data center or power plant of type r at location l. $DC\_Cost(l)$, $RE\_Cost(l, r)$ and $Grid\_Cost$ represent the cost for data centers, renewable plants and the power grid system respectively.

The overall cost should be optimized under the constraints, which are listed in Figure 9. Equation 21-23 show the constraints of the provisioned capacity for data centers. Equation 24 means that the provisioned capacity for rewnewble energy plants are determined by the total power demand from the data centers. This constraint is added indicating that the power generation and consumption added to the grid should be balanced from the perspective of the grid system. Furthermore, Equation 26 is a strict limitation for keeping the grid out of any violations at any given time t, since we assume the grid reliability is crucial and must be guaranteed.

TABLE III: Parameters for placement framework. Each location l is a possible location from the set $\mathcal{L}$, and each t denotes a time epoch during a time period T. Each r is a type of renewable energy from the set $\mathcal{R}$.

Symbol	Meaning	Unit
$CapapcityDC$	desired computational power of the DC network	kW
$landPrice(l)$	the price of buying land at location l	\$/m^2
$costLineGrid(l)$	the cost to layout power line to connect data center at location l to the power grid	\$
Data center		
$areaDC$	land area needed per unit of DC capacity	m^2/kW
$priceBuildDC(c)$	price of building a data center with computational power capacity c	\$/kW
$numServers(l)$	the number of servers bought and put at location l	#
$numSwitch(l)$	the number of switches bought and put at location l	#
$priceServer$	the price of each server in the data center	\$/serv
$priceSwitch$	the price of each network switch in the data center	\$/switch
$costLineNet(l)$	the cost to layout optical fiber to connect data center at location l to the network	\$
$priceBWServer$	the cost of external network bandwidth per server	\$/serv-month
$PUE(l, t)$	the PUE at location l during timp epoch t	
$maxPUE(l)$	the maximum PUE at location l	
$priceEnergy(l)$	the price of using energy from the power grid at location l	\$/kWh
$demand(l, t)$	average computing power demand of data center at location l during time epoch t	kW
Renewable energy power plant		
$areaRE(r)$	land area needed per unit of power plant of renewble energy type r	\$/m^2
$priceBuildRE(c, r)$	the price of building a renewable energy power plant of type r	\$
$revEnergy(l)$	the unit revenue by providing energy to the power grid at location l	\$/kWh
$effRE(r, l, t)$	the power generation efficiency of renewable energy type r at location l in time epoch t	%
$avgEff(r, l)$	the average generation efficiency of reneable energy type r at location l	%
Grid operation		
$transLoss(t)$	the thermal losses in line tranmission and power flow during time epoch t	kW
$disLoss(t)$	the losses for distributing power to data center during time epoch t	kW
$priceLoss$	the price for transimission losses per kWh	\$/kWh
$numLineVio(t)$	the number of line capacity violation during time epoch t	#
$numVolVio(t)$	the number of voltage level violation during time epoch t	#
Decision Variables		
$DC(l)$	1 if a datacenter placed at location l, otherwise 0	bool
$capDC(l)$	the max computational power capacity deployed for data center at location l	kW
$RE(l, r)$	1 if a renewable energy power plant of type r placed at location l, otherwise 0	bool
$capRE(l, r)$	the built capacity of the renewable energy power plant of type r at location l	kW

$$
\begin{aligned}
TotalCost &= \sum_{l\in\mathcal{L}} DC(l)\cdot DC\_Cost(l) + \sum_{l\in\mathcal{L},r\in\mathcal{R}} RE(l,r)\cdot RE\_Cost(l,r) + Grid\_Cost && (2)\\
DC\_Cost(l) &= DC\_CAPcost(l) + DC\_OPcost(l) && (3)\\
DC\_CAPcost(l) &= DC\_landCost(l) + DC\_buildCost(l) + DC\_hwCost(l) && (4)\\
DC\_OPcost(l) &= DC\_netCost(l) + DC\_energyCost(l) && (5)\\
DC\_landCost(l) &= landPrice(l)\cdot areaDC\cdot capDC(l) && (6)\\
DC\_buildCost(l) &= capDC(l)\cdot maxPUE(l)\cdot priceBuild(capDC(l)\cdot maxPUE(l)) && (7)\\
DC\_hwCost(l) &= DC\_serverCost(l) + DC\_switchCost(l) + costLineGrid(l) + costLineNet(l) && (8)\\
DC\_serverCost(l) &= numServers(l)\cdot priceServer && (9)\\
DC\_switchCost(l) &= numSwitch(l)\cdot priceSwitch && (10)\\
DC\_netCost(l) &= numServers(l)\cdot priceBWServer && (11)\\
DC\_energyCost(l) &= \sum_{t\in T} t\cdot priceEnergy(l)\cdot demand(l,t) && (12)\\
RE\_Cost(l,r) &= RE\_CAPcost(l,r) - RE\_OPrev(l,r) && (13)\\
RE\_CAPcost(l,r) &= RE\_landCost(l,r) + RE\_buildCost(l,r) + costLineGrid(l) && (14)\\
RE\_landCost(l,r) &= landPrice(l)\cdot area(r)\cdot capRE(l,r) && (15)\\
RE\_buildCost(l,r) &= priceBuildRE(capRE(l,r),r)\cdot capRE(l,r) && (16)\\
RE\_OPrev(l,r) &= revEnergy(l)\cdot \sum_{t\in T} t\cdot effRE(r,l,t)\cdot capRE(l,r) && (17)\\
Grid\_Cost &= priceLoss\cdot \sum_{t\in T} t\cdot (transLoss(t) + disLoss(t)) && (18)\\
DC(l) &= \begin{cases} 1 & \text{if a data center is located at } l \\ 0 & \text{otherwise} \end{cases} && (19)\\
RE(l,r) &= \begin{cases} 1 & \text{if building a renewable energy plant of type } r \text{ at } l \\ 0 & \text{otherwise} \end{cases} && (20)
\end{aligned}
$$

Fig. 8: Optimization framework.

C. Optimizing approaches

1) Semi Brute force: A time-consuming approach is to generate all of the possible combinations for data centers and renewable energy plants. However, it is not possible to generate all kinds of capacity provisioning amounts since it's not discrete. Thus, we generate combinations of locations first, and then evenly distribute the total capacity to all of the candidate locations selected. By testing these generated configurations, the approach returns the best one with the lowest total cost. This approach still could be very exhaustive, which needs extremely long time for execution.

2) Heuristic searching: XW: TO DO SOME WORK...

IV. Evaluation Experiment

Now in this section, we study the overall cost for placing data centers and renewable energy power plants into the same grid network. By considering the grid loss or not, we can get different results of placement decisions.

A. Input data

The target area here is New England in United States, and we select 56 locations as candidates inside this area, as shown in Figure 10. We obtained the Typical Meteorological Year (TMY) information for 56 locations from US Department of Energy (2), which includes a one-year dataset of hourly weather values for a location. We simplify the problem by only considering one type of renewable energy - wind. We computed the average wind power generation using $effRE(l,t)$ derived from the specifications for the 1.5MW Series wind turbine from General Electric Company [22], TMY wind speed, TMY air pressures, and conversion losses.

Besides, we collected various data of PUEs, data center construction costs, wind farm construction costs, land costs, transmission lines and network connection costs and grid energy costs in the same way as stated in [17]. Specifically, for grid costs, we use $priceLoss$ the same as the maximum electricity price in the whole area. The input data for the grid is derived from the New England grid system, which is shown as in Section II,including all of the settings for buses, branches and generators in it. Thus, the transimission loss, $transLoss(t)$, could be computed by simulating the power flow process for timp epoch t. According to the study in [23], we set the distribution loss as 3% of the average power generation of the added power plant.

$$
\begin{aligned}
\forall_{l\in\mathcal{L}}, capDC(l) \leq DC(l)\cdot CapacityDC &\Rightarrow \text{capacity of data center at } l \text{ should be zero when } DC(l) \text{ is } 0 && (21)\\
\sum_{l\in\mathcal{L}} DC(l)\cdot capDC(l) = CapacityDC &\Rightarrow \text{total capacity of built data centers should meet the requirement} && (22)\\
\forall_{t\in T}, demand(l,t) \leq capDC(l) &\Rightarrow \text{power demand of the data center should not exceed its capacity} && (23)\\
\sum_{l\in\mathcal{L}, r\in\mathcal{R}} RE(l,r)\cdot capRE(l,r)\cdot avgEff(l,r) = & \\
\sum_{t\in T, l\in\mathcal{L}} DC(l)\cdot demand(l,t)\cdot PUE(l,t) &\Rightarrow \text{the generated green energy should be balanced with consumption} && (24)\\
\forall_{t\in T}, 0 \leq effRE(r,l,t) < 1 &\Rightarrow \text{efficiency of power plant should be between } [0,1) && (25)\\
\forall_{t\in T}, numLineVio(t) = 0, numVolVio(t) = 0 &\Rightarrow \text{No violations in each time epoch} && (26)\\
& && (27)
\end{aligned}
$$

Fig. 9: Optimization constraints.

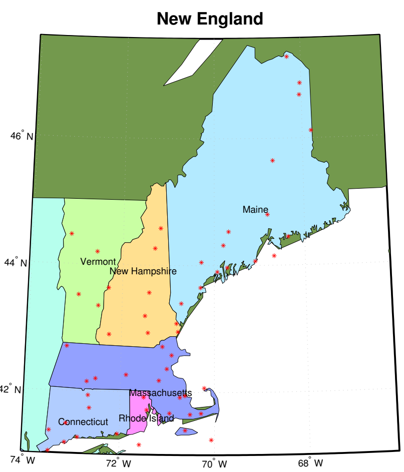


Fig. 10: Candidate locations in New England

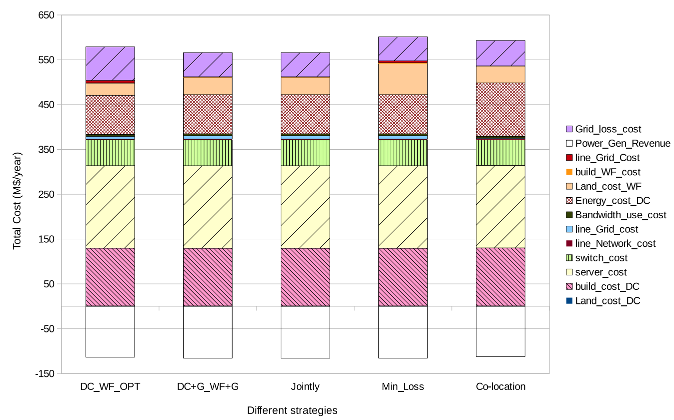


Fig. 11: Costs of building one data center (100MW) with one wind farm

B. Building one data center with one wind farm

Here, we are trying to solve a simplest case of the defined problem by placing only one data center and only one wind farm onto the grid system. The added generation (wind power) and consumption (data center load) should be balanced for the grid to keep reliability to the best extent. In this case, we can brute force all of the combinations of locations for the data center and the wind farm. Figure 11 shows the results of the total cost by using five different strategies when seeking the best locations when we are building a 100MW data center and a wind farm which can supply green energy for it.

The five different strategies are explained as follows:

(1)**DC_WF_OPT.** This strategy tries to seek for the best location for the data center where its total cost could be minimized, and the best location for the wind farm where its total cost could be minimized. Grid costs are not considered here.

(2)**DC+G_WF+G.** Since only putting data center or wind farm into the grid will change the power flow, this strategy tries to add the transimission loss costs into consideration when seeking for best locations separately for the data center and the wind farm.

(3)**Jointly.** All of the combinations of locations are exploited by using this strategy to seek for the jointly placement choice for both the data center and the wind farm, considering the total cost as calculated by Equation 2.

(4)**Min_Loss.** Here, this strategy seeks for the locations for data center and wind farm which can lead to the minimal grid losses cost, including both transmission losses and distribution losses.

(5)**Co-location.** Assuming the the data center should be build together with an on-site wind farm, this strategy seeks for one location to place both the data center and the wind farm towards miniming the total cost.

From the figure, we can see that by considering grid costs, the total cost will be further saved compared to best choices for the data center and the wind farm separately. Also, Min_Loss can achieve minimal losses of all possible choices, but the total cost is large mainly because it selects an expensive place for purchasing land for the wind farm. The best choice of co-location options is also nearly 7% higher than the *Jointly* choice, and it's easy to understand since the best location for data center is not necessarily the best for wind farm and vice versa.

We calculate all of the combinations for wind farm and data center locations and use the average total cost of these combinations (which is $667.1M per year) as the baseline for comparison. Then, the locations found and the corresponding cost savings of the five strategies are listed in Table IV.

TABLE IV: Detailed results of cost savings by different strategies.

Strategy	Data center location	Wind farm location	Total cost (M$/year)	Cost saving (%)
DC_WF_OPT	Burlington,NH	Mount Washington, NH	465.6	30.2
DC+G_WF+G	Springfield Hartnes, VT	Nash Island, CO	450.3	32.5
Jointly	Springfield Hartnes, VT	Nash Island, CO	450.3	32.5
Min_Loss	Springfield Hartnes, VT	Marthas Vineyard, RI	485.6	27.2
Co-location	Nash Island, CO	Nash Island, CO	480.7	27.9

C. Multiple data centers and wind farms

XW: NEED MORE MORE WORK....

V. Related Work

This section reviews relevant work to this paper in the recent literature, which are classfied into two categories.

A. Effect of data centers to the grid

In the smart grid era, data centers began to show the advantages for demand response and facilitate ancillary services due to its great and controllable flexibility. Researchers studied the effect of datacenter demand response on power consumption reduction [24], [25]. They found that 25% of the demand savings can be done with minimal or no impact on datacenter performance. Also, 10% of the load can be shed with short response time with no operational impact. They did not consider dynamic load migration of the workload which can result in further reduction in power demand.

Mohsenian *et al.* in [26] proposed a request distribution policy among datacenters to ensure power load balancing. They tried to minimize the maximum power on any transmission line by distributing the computing requests to suitable datacenter. Their work assumes that a fairly large number of datacenters (e.g. 6) are connected to the same power distribution network. In practice, it is very rare for some company to build several datacenters connected to the same power distribution network. Aikema *et al.* in [27] studied the energy cost savings that can be achieved when datcenter participates in ancillary services. Their simulation shows that 12% cost savings can be done at the cost of 2% performance loss (i.e. increased latency).

Recently, Wierman *et al.* [28] surveyed the opportunies and challenges for data centers to ease the incorporation of renewable energy source into the grid and shaving the peak load. Further, Liu *et al.* in [29] focused on the impact of datacenter demand response on grid. They concluded that datacenter demand response can reduce the storage requirement of a grid with renewable energy source. The other key finding of their work is voltage violation frequency is lower when datacenter is placed on the same power bus with the PV solar source.

Different from these work, we quantify the data center impact on the grid by focusing on the losses brought because of penetrating additional load and generations to the grid network in a regional area. By incorporating such effects into a holistic framework, we convert such losses to grid operational costs and regard it as part of the total cost when building and planning the capacity of data centers and also the renewable energy power plants.

B. Datacenter placement and capacity planning

Some prior work has discussed about the placement issues of data centers. Alger [13] explained how to choose an optimal location for the data center several years ago, by considering hazars, accessibility and scalability factors. Stansberr [30] ranked some cities by estimating the annual operation costs of the data center. Oley [14] considered looking for a proper location for the data center establishment only by investigating the power rates of different states. Goiri *et al.* [12] focused on intelligently finding the best places for building multiple data centers to form a network for interactive Internet services. This work is to some extent close to ours, but they didn't consider the provisioning issues of renewable energy plants and the relevant costs.

Larumbe *et al.* [15] presented a mathematical problem aiming at solving the location and routing of cloud service components. Gao *et al.* [31] studied how to sit data centers near existing wind farms, and distributing load using a greedy online algorithm. Berral *et al.* [17] considered to select sites for data centers and on-site power plants aiming at follow-the renewable cloud services. Unlike our work, they didn't put insights the possible impact of data centers and distributed energy generations on the utility grid system.

Different from these work, we quantify and incorporate the impact of the site selection on the grid operation, and regard the summarized cost as the objective, which shows the importance of collaboring service providers and grid operators together to do the site and capacity planning.

VI. Conclusion

In this paper, we studied the problem of smartly placing green data centers in proper locations with considering the impact on electricity grid. Since connecting data centers and renewable energy plants to the utility grid will change the power flow of the whole grid network, and thus the transmission losses and distribution losses should be incorporated when trying to minimize the total cost. In this context, we proposed an optimization framework with the purpose of optimizing the total cost including data center, renewable energy plant and also the grid cost. The problem is formulated with several necessary constraints according to the reliablity issues for the grid. By solving the problem, we tried to seek for best locations for sitting and provisioning the capacity of both data centers and renewable energy plants. Our optimization results show that considering the grid cost will have different impact on the placement choice for sitting data centers and renewable power plants. This means grid-aware placement stategies could further help saving the overall cost from the perspective of both IT companies and grid operators.

REFERENCES

[1] R. Urgaonkar, B. Urgaonkar, M. J. Neely, and A. Sivasubramaniam, "Optimal power cost management using stored energy in data centers," in *SIGMETRICS*, 2011.

[2] J. Koomey, *Growth In Data Center Electricity Use 2005 To 2010*. Oakland, CA: Analytics Press, 2011.

[3] G. Ghatikar, "Demand response opportunities and enabling technologies for data centers: Findings from field studies," 2014.

[4] Google, "Renewable energy Data Centers Google," 2014, http://www.google.com/about/datacenters/renewable/.

[5] Apple, "Apple and the Environment," 2013, http://www.apple.com/environment/renewable-energy/.

[6] R. Miller, "Data Centers Scale Up Their Solar Power," 2012, http://www.datacenterknowledge.com/archives/2012/05/14/data-centers-scale-up-their-solar-power/.

[7] I. Goiri, W. Katsak, K. Le, T. D. Nguyen, and R. Bianchini, "Parasol and GreenSwitch: Managing Datacenters Powered by Renewable Energy," in *ASPLOS*, 2013.

[8] Julfikar Ali Manik and Nida Najar, "Electricity Returns to Bangladesh After Power Failure," 2014, http://www.nytimes.com/2014/11/02/world/asia/power-grid-failure-puts-bangladesh-in-the-dark.html.

[9] H. Wang, J. Huang, X. Lin, and H. Mohsenian-Rad, "Exploring smart grid and data center interactions for electric power load balancing," *SIGMETRICS Perform. Eval. Rev.*, vol. 41, no. 3, pp. 89–94, Jan. 2014. [Online]. Available: http://doi.acm.org/10.1145/2567529.2567556

[10] R. de Groot, J. Morren, and J. Slootweg, "Investigation of grid loss reduction under closed-ring operation of mv distribution grids," in *PES General Meeting— Conference & Exposition, 2014 IEEE*. IEEE, 2014, pp. 1–5.

[11] U.S. Energy Information Administration, "How much electricity is lost in transmission and distribution in the United States?" 2014, http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3.

[12] I. Goiri, K. Le, J. Guitart, J. Torres, and R. Bianchini, "Intelligent Placement of Datacenters for Internet Services," in *ICDCS*, 2011.

[13] D. Alger, "Choosing an Optimal Location for Your Data Center," in *InformIT*, 2006.

[14] B. Oley, "Power & Approaching the Best Place to Build a Data Center," pp. 32–33, 2009.

[15] F. Larumbe and B. Sansò, "Optimal Location of Data Centers and Software Components in Cloud Computing Network Design," in *CCGrid*, 2012.

[16] K. Le *et al.*, "Capping the Brown Energy Consumption of Internet Services at Low Cost," in *IGCC*, 2010.

[17] J. L. Berral, I. Goiri, T. D. Nguyen, R. Gavalda, J. Torres, and R. Bianchini, "Building green cloud services at low cost," in *Distributed Computing Systems (ICDCS), 2014 IEEE 34th International Conference on*. IEEE, 2014, pp. 449–460.

[18] Seifi, Hossein, Sepasian, Mohammad Sadegh, *Electric Power System Planning*. Springer, 2011.

[19] G. Bills *et al.*, "On-line stability analysis study," *Report for the Edison Electric Institute RP90-1*, 1970.

[20] Data Center Research, "Data Center Map," 2014, http://www.datacentermap.com/datacenters.html.

[21] Y. Lei, A. Mullane, G. Lightbody, and R. Yacamini, "Modeling of the wind turbine with a doubly fed induction generator for grid integration studies," *Energy Conversion, IEEE Transactions on*, vol. 21, no. 1, pp. 257–264, 2006.

[22] General Electric Company, "1.5 MW Wind Turbine Technical Specifications," 2013, http://site.ge-energy.com/prod_serv/products/wind_turbines/en/15mw/specs.htm.

[23] B. Amanulla, S. Chakrabarti, and S. Singh, "Reconfiguration of power distribution systems considering reliability and power loss," *Power Delivery, IEEE Transactions on*, vol. 27, no. 2, pp. 918–926, April 2012.

[24] V. Ganti and G. Ghatikar, "Smart Grid as a Driver for Energy-Intensive Industries: A Data Center Case Study," 2012, lBNL.

[25] G. Ghatikar, V. Ganti, N. Matson, and M. A. Piette, "Demand Response Opportunities and Enabling Technologies for Data Centers: Findings from Field Studies," 2012, lBNL.

[26] A.-H. Mohsenian-Rad and A. Leon-Garcia, "Coordination of Cloud Computing and Smart Power Grids," in *2010 First IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 2010, pp. 368–372.

[27] D. Aikema, R. Simmonds, and H. Zareipour, "Data centres in the ancillary services market," in *IGCC*, 2012, pp. 1–10.

[28] I. L. Adam Wierman, Zhenhua Liu and H. Mohsenian-Rad, "Opportunities and Challenges for Data Center Demand Response," in *Proceedings of IEEE IGCC, 2014.*, 2014. [Online]. Available: http://users.cms.caltech.edu/~adamw/papers/dcdrsurvey.pdf

[29] Z. Liu, I. Liu, S. Low, and A. Wierman, "Pricing data center demand response," in *Proc. ACM Sigmetrics*, 2014.

[30] M. Stansberr, "Data Center Locations Ranked by Operating Cost," in *SearchDatacenter.com*, 2006.

[31] Y. Gao, Z. Zeng, X. Liu, and P. Kumar, "The Answer Is Blowing in the Wind: Analysis of Powering Internet Data Centers with Wind Energy," in *INFOCOM*, 2013.