2012 IEEE 20th International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems

Carbon-Aware Energy Capacity Planning for Datacenters

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***Abstract*—Datacenters are facing increasing pressure to cap their carbon footprints at low cost. Recent work has shown the significant environmental benefits of using renewable energy for datacenters by supply-following techniques (workload scheduling, geographical load balancing, etc.) However, all such prior work has only considered on-site renewable generation when numerous other options also exist, which may be superior to on-site renewables for many datacenters. Alternative ways for datacenters to incorporate renewable energy into their overall energy portfolio include: construction of or investment into off-site renewable farms at locations with more abundant renewable energy potential, indirect purchase of renewable energy through buying renewable energy certificates (RECs), purchase of renewable energy products such as power purchase agreements (PPAs) or through third-party renewable providers. We propose a general, optimization-based framework to minimize datacenter costs in the presence of different carbon footprint reduction goals, renewable energy characteristics, policies, utility tariff, and energy storage devices (ESDs). We expect that our work can help datacenter operators make informed decisions about sustainable, renewable-energy-powered IT system design.**

I. Introduction

The growth in the scale and number of datacenters is raising serious concerns about their power consumption. In 2005, the EPA [33] projected datacenter power demands to double by 2010. Though the recent Koomey report [22] has scaled down this growth to 56% (attributed to hardware improvements and increasing adoption of best practices), the cost of powering the U.S.'s datacenters is still expected to exceed $15 billion over the next decade and impose a peak load of over 20GW on the grid. Each 100MW power plant costs $60-100 million to build and emits over 50 million tons of CO_2 over its lifespan [14]. If datacenters were to be treated as a country, they would be the fifth largest electricity consumers across the world today [12].

Their high power consumption has two serious consequences for datacenters. First, generating and delivering this power to the datacenter, especially for its peak capacities and at times-of-day when there is high demand elsewhere, results in a high monthly electricity bill. A large datacenter may face millions of dollars annually in power-related operational expenditures. Second, much of the current grid power in many geographies is still heavily dependent on burning fossil fuels. Similar to other large consumers of power, datacenters find themselves increasingly pressured (either through legislation or simply public opinion) to find options to reduce their carbon footprint. Demand reduction is one obvious way of addressing both these concerns, and there have been numerous academic and commercial endeavors for achieving this with better energy-proportional computing technologies (consolidation and server shut down, deeper sleep states, and power mode control of IT equipment), improving power delivery efficiencies, and more efficiently controlling the cooling systems, over the past decade. Over and beyond demand reduction, datacenters are continuing to explore options for further reducing power related costs and their carbon footprints.

A complementary way of addressing these issues is with smarter electricity sourcing strategies. One is no longer necessarily tied to source from the grid. Capital costs of deploying renewable energy generation equipment (e.g., wind turbines, solar panels) have become increasingly attractive (especially with incentives in several geographies). These equipments could be deployed on-site (captive generation) at the datacenter facility itself, e.g., the Green House Data wind-powered datacenter [19] and Facebook's solar-powered datacenter [15]. The advantages of such on-site generation include negligible transmission and distribution losses, and perhaps even the ability to tolerate an outage on the regular grid. However, it is not necessary that the best location for a datacenter (which can be a function of numerous other factors including network latencies, labor force availability, tax structures, etc.) necessarily has the right renewable energy potential for a profitable on-site renewable deployment.

Another model is to locate the renewable energy generation plant at an off-site facility (with good wind speed or solar irradiation), and "wheel" the generation across the grid to the consuming datacenter. In this model, along with transmission losses, there could be wheeling (and banking) charges imposed by the grid, though the generation potential may be much superior because of the flexibility to locate the generation in a more conducive location. In both these models, the mismatch between the production/supply and the consumption/demand may warrant consideration of explicit energy storage, and costs for this storage (either in explicitly procuring and managing storage devices such as batteries, or payment of banking charges to the grid) will need to be considered.

Whereas the above options require *explicit* involvement of the datacenter in provisioning renewable generation plants, there also exist a number of *implicit* options to achieve the same result. With one such set of options, a datacenter can purchase various renewable electricity products. One example

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DOI 10.1109/MASCOTS.2012.51

is a power purchase agreement (PPA), buying a portion of the "green" power output from a renewable energy project in a long-term contract. Alternatively, a datacenter can simply procure its desired "blended" power mix from a third party provider at the applicable tariff. Such offerings may themselves come from a mix of "black" (i.e., fossil fuel based) and "green" (i.e., renewable) power sources - we refer to such a mix of black and green power sources as "brown." These renewable electricity products may be attractive since they eliminate the need for capital and operational investments for running renewable power plants, and perhaps also offer immunity to the variability inherent in renewable generation. Another set of implicit options is based on *carbon offsetting*, either through accredited CDM (Clean Development Mechanism) projects in developing countries or through purchase of carbon credits or renewable energy credits (RECs) in the open market. The merits of these implicit options, particularly the latter, are subject to the vagaries of a continuously evolving market.

Given all these choices, along with the vagaries of renewable energy generation capacity, variances in datacenter demand, and market price fluctuations, energy capacity planning becomes difficult. It is exactly this problem that this paper addresses by presenting an optimization framework to help a datacenter achieve a target carbon footprint at minimal cost.

We evaluate this optimization framework with a diverse range of datacenter power profiles, different procurement/offset mechanisms, and different kinds of generation efficiencies for both on-site and off-site renewables using traces from National Renewable Energy Laboratory (NREL) [30]. Our evaluations show several interesting insights:

- Contrary to expectations, renewable penetration in the datacenter operations can actually lower costs, not just lower carbon footprints. Unless a datacenter wants to achieve a very low carbon footprint, it can realize cost savings from renewable sourcing options - either on-site or off-site.
- Most prior studies have looked at on-site renewables without considering the impact of "peak shaving." In fact, this turns out to be one of the best ways renewables help to lower costs. Furthermore, such on-site renewables can supplement/replace energy storage devices (ESDs) or traditional captive sources (e.g., diesel generators) in their role in peak reduction but at a lower cost.
- The most cost-effective options for carbon reduction varies depending on how much carbon reduction is desired. Previously studies have not really considered decision-making across a spectrum of carbon-reduction targets. On-site generation is preferable when the targets are not that stringent (say up to 30%), but beyond that off-site becomes more cost-effective. A hybrid of these two options is the most cost-effective across the spectrum.

II. Background on Renewables for Datacenters

In this section, we provide background on datacenter power infrastructure and various options based on explicit or implicit incorporation of renewable energy for a datacenter to meet its carbon offsetting targets (if any) and/or cost-savings. Throughout the section, we follow up general concerns related to an aspect with specific assumptions or simplifications we make in our formulation.

A. Datacenter Power Infrastructure

Power enters the datacenter through a utility substation, which acts as its primary power source. Datacenters also employ diesel generators (DG) as a secondary backup power source. A typical datacenter power infrastructure consists of a hierarchy of power supply/distribution elements. Given our focus on decision-making related to renewable incorporation, rather than considering datacenter design completely from scratch, we focus on a datacenter that is already designed in the following sense: our datacenter's IT, cooling, and power infrastructure have already been provisioned based on well-established capacity planning techniques, but without employing any renewable energy options. Treating this datacenter as a *given* and a *black box*, we are interested in the subsequently arising capacity planning problem of choosing from among various explicit and implicit renewable energy options available to this datacenter. Our setting, therefore, captures an existing datacenter interested in altering its carbon footprint without the option of modifying its internal infrastructure. Studying the problem of joint capacity planning of the datacenter's IT, cooling, and power infrastructure with its renewable energy portfolio is part of our future work. Figure 1 captures this setting and shows different options for renewable incorporation.

B. Carbon Offsetting Targets

Many carbon cap policies and regulations are being deployed worldwide. They may be government-mandated, utility-imposed, or voluntary. For example, under European Union Emissions Trading System (EU ETS), the governments of the EU member nations agree on national emission caps. Large carbon emitters in these countries must monitor their CO_2 emissions and report them annually to the government. Those who fail to offset or reduce their carbon footprints to comply with the carbon regulations face penalties. An alternative policy is based on the notion of a *carbon tax*, an environmental tax levied on corporate carbon footprints. As big power consumers, datacenters are facing increasing pressure to cap their carbon footprints. The life cycle carbon footprint of a datacenter includes the carbon emissions during the processes of IT equipment manufacturing and renewal (servers, UPS, cooling, etc.) and datacenter operation (which includes the electricity drawn from the utility).

What We Model and Study: We focus only on the carbon footprint of the datacenter operation in this study (i.e., the carbon emissions associated with its electricity consumption). We incorporate a carbon constraint in our framework which requires that the carbon emission associated with electricity consumption be reduced by a certain percentage compared to default sourcing of all energy from the grid, i.e., a specified fraction of the datacenter's overall electricity consumption is

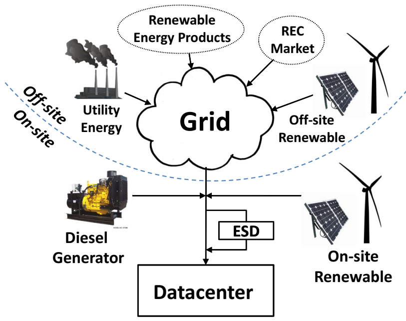

Fig. 1. Various renewable options available to a datacenter in our study. We assume a datacenter whose internal IT, cooling, and power infrastructure have been provisioned, and which must now make capacity planning decisions for on-site/off-site renewable generation and energy storage. The datacenter may also employ implicit renewable options such as RECs and renewable energy products to incorporate renewables into its overall energy portfolio.

required to be "green" (carbon-free). In order to evaluate the amount of carbon emission by different power sources, we use the notion of the *carbon emission factor* (denoted as ϵ) which measures the amount of CO_2 (grams) released per unit electricity (kWh) generated by a power resource [1].

C. Explicit Renewable Energy Options

We classify the renewable energy options where the datacenter is explicitly involved in managing energy sources (which it may own itself or may "rent" from other entities) into two categories: on-site versus off-site renewable generation.

On-site Renewable Generation: Increasingly, datacenters are installing renewable generators within their own facilities, with wind and solar being the most popular options. All or a portion of the energy generated by these on-site renewable sources can be used to augment the datacenter's power draw from the utility. It may also be possible for the datacenter to "sell" portions of this energy to the grid based on a buy-back scheme offered by some utilities. E.g., in the U.S., net metering [32] allows electric customers who generate their own electricity using solar energy (or other forms of renewable energy) to sell back to the grid at *utility buy-back price*. It may also be desirable for the on-site source's power to be stored - in the on-site ESD shown in Figure 1 - so that it can be used/sold at a more opportune time in the future. Provisioning this ESD is particularly important to bridge any temporal mismatch between the datacenter's power needs and the on-site renewable's supply. The ESD may also allow the datacenter to improve how it avails of a buy-back scheme offered by the utility in cases where the buy-back price is time-varying.

Off-site Renewable Generation: Although on-site renewable generation is becoming increasingly appealing, it may not always be the best renewable option for a datacenter due to reasons described in Section I, and an off-site location which better suits the renewable technology may be preferable. With off-site renewable generation, the grid essentially acts as the "carrier" of the energy produced at that location for which the utility charges the datacenter a fee; the datacenter is incentivized for its contribution of renewable energy via some form of discount in its utility bill. Certain accounting and charging mechanisms must be provided by the utility provider to record the energy contributed by the off-site source to the grid and incorporate this into the utility bill for the datacenter. This is realized by using two mechanisms called *wheeling* and *banking*. Wheeling refers to the grid transporting the power generated by the off-site source. In places where wheeling is allowed, different charging mechanisms for providing this service exist. In one popular mechanism that we consider in our work, the utility charges the datacenter for the market-price of a fraction f of the power generated at the off-site location during a billing cycle (typically a month). The remaining power is then effectively provided to the datacenter for "free." An example of this is the wheeling model used in the state of Tamilnadu in India where f=5% [36]. Banking refers to a service offered by the utility to carry over any excess energy generated by the off-site source (compared to what was used by the datacenter) across billing cycles. The utility provider then charges the datacenter for this based on the amount of excess energy (e.g., market price of 5% of the excess energy in Tamilnadu).

What We Model and Study: We explore the provisioning of wind and solar based renewable generation along with ESD based on UPS units possessing lead-acid batteries for on-site renewables. We incorporate both wheeling and banking of the electricity generated off-site, and study the impact of a wide range of wheeling charges in our evaluation. To keep our evaluation simple, we do not consider ESD provisioning at the off-site location (mainly because using the grid as a "virtual ESD" via wheeling typically beats explicit ESD provisioning cost-wise). However, as will be apparent to the reader in Section III, our framework can be easily extended to include this.

D. Implicit Renewable Energy Options

Numerous ways now exist for a datacenter to implicitly incorporate renewable energy into its overall energy consumption portfolio. In these options, the datacenter is not an active participant in the provisioning and operation of the energy source, but rather avails of renewable energy generated by other entities by paying them in some fashion. We now discuss the most important mechanisms of this kind.

Renewable Energy Certificates: A Renewable Energy Certificate (REC), also known as a "green certificate" or a "renewable energy credit," represents the generation of one MWh of electricity from an eligible renewable source. RECs are classified into "tiers" based on the underlying renewable sources in many states in the U.S. to comply with state renewable energy portfolio standard. E.g., in Maryland, RECs fall into tier I, tier II and solar REC [32]. In our work, we ignore these distinctions and consider all RECs as tier-1. RECs are tradable commodities in REC markets and are sold separately from the underlying physical electricity. Purchasing a REC allows one to claim that the corresponding portion of its overall energy consumption was "green." Finally, if a datacenter employs on-site or off-site renewable generation, it can derive RECs through an audit/accreditation process, which the datacenter can choose to sell on the REC market. We also incorporate this feature in our formulation.

Renewable Energy Products: One type of renewable energy product is the Power Purchase Agreement (PPA). PPA is a contract between a consumer and a renewable energy producer which allows the consumer to purchase a portion or all of electricity generated by the producer at a negotiated price for which it accumulates some form of credits such as RECs. For example, Google contracted to buy 114MW of wind power for 20 years from a wind project in Ames, Iowa to power Google's datacenter in Council Bluffs, Iowa [3]. Microsoft bought wind power to power part of its 22.2MW datacenter in Dublin, Ireland [4]. Datacenters may also choose to buy their desired mix of green and brown energy from their electricity provider or a third party provider. For example, in the U.S., customers may be able to buy a green pricing/green marketing product from local utility by paying a premium on their electric bills [2]. A renewable product can be in terms of fixed green energy quantity or a blended green and brown energy with certain percentage of green guaranteed.

Power Sources	Utility	PPA	REC	DG
Unit Cost(¢/kWh)	5	6	0.5	30
Emission Factor (gram CO_2e/kWh)	586	0	0	1056

TABLE I
COST AND CARBON EMISSION COMPARISON OF THE ENERGY SOURCES OTHER THAN SOLAR AND WIND THAT WE CONSIDER IN OUR WORK [20], [1].

What We Model and Study: Of the above mechanisms, we incorporate the two most prominent - RECs and PPAs - into our framework in Section III and evaluate their impact in Section IV. Table I shows the utility price, REC, PPA price and the op-ex cost of on-site diesel generator on datacenter facilities. For simplicity, these costs are assumed to be constant in our experiments. Table I also presents the typical carbon emission factors for these sources.

E. *Salient Properties of Wind and Solar Sources*

Wind and solar are the most prominent sources of renewable energy today and currently account for 62% and 13% of the non-hydro renewable electricity generation worldwide, respectively [16]. The effective power output of solar/wind-based sources is closely tied to certain environmental conditions (e.g., wind speed and solar irradiance), and hence, can be highly time-varying. Consequently, their *capacity factor* - the ratio of the actual power output during a given period to the maximum potential output if operated at full nameplate/rated capacity - can be substantially lower than that of conventional power plants. Due to their access to adequate supplies of fossil fuels, conventional power plants can have capacity factors of 80% or higher. On the other hand, capacity factors for wind and solar sources are much lower.

The capacity factor of wind energy ranges from 20% to 45% depending on average annual wind speeds, with an average capacity factor of 30% in the U.S. in 2010 [40]. The cost of wind energy is dominated by upfront installed cost, i.e., capital expenditure or "cap-ex." It accounts for 75% of the lifetime total cost. Wind energy is capital-intensive compared to conventional fossil fuel fired technologies such as a natural gas power plant, where as much as 40% to 70% of costs are related to fuel, operation and maintenance (O&M), i.e., operational expenditure or "op-ex."

For solar energy, we consider the solar photovoltaic (PV) system. The capacity factor of PV ranges from 14% (e.g., in Seattle) to 24% (e.g., in Phoenix) [31]. PV is much more expensive than wind and other renewable technologies [7]. Similar to wind, the O&M cost is only a small fraction of PV systems' life cycle cost. Table II shows the parameters of wind and PV system we use in our evaluation. Note that O&M cost is averaged over the generator's lifetime.

Renewable Type	Wind	PV
Installed Cost ($/kW)	2,200	6,000
O&M Cost (¢/kWh)	1	1
Utility Buy-back Price (¢/kWh)	2	2
Life Time (yr)	20	25
Life Cycle Emission Factor (gram CO_2e/kWh)	29	53

TABLE II
SALIENT CHARACTERISTICS OF WIND AND SOLAR GENERATION SOURCES THAT WE USE IN OUR EVALUATION [7], [40].

Perhaps the most prominently touted advantage offered by renewable sources is that their operation is free of carbon emissions and most other forms of pollution. This is, however, a simplified view that ignores carbon emissions that occur during the manufacturing, transportation, installation, and recycling of equipment used in these renewable sources. Compared with the emission factor of utility electricity (586 g CO_2/kWh), although wind (29 g CO_2/kWh) and solar (53 g CO_2/kWh) are much lower, we consider these factors in the decision-making since they matter at high carbon reduction goals.

What We Model and Study: One key difficulty in greening data centers cost-effectively can arise from the very lack of enough renewable generation capacity [21], [38]. We should emphasize that our work ignores this difficulty and we do not incorporate upper bounds on the renewable electricity available to a datacenter in our formulation. Consequently, the insights in our evaluation must be qualified as applying to datacenters located in regions with access to enough renewable capacity (whether explicit or implicit). A related issue is that renewable electricity may be too expensive in certain geographies due to high demand for it relative to generation. While our framework is capable of dealing with high costs for renewables, in our evaluation, we restrict our attention to costs represented by sources mentioned in Table II.

III. OUR OPTIMIZATION FRAMEWORK FOR PROVISIONING AND SOURCING RENEWABLES

In this section, we develop a linear programming based framework for a datacenter to incorporate renewables into its overall energy mix in a cost-effective and/or carbon-sensitive manner from among the various options presented in Figure 1.

A. Inputs

Workload Power Demand: Given extensive prior work on load prediction and power modeling , we assume sufficiently accurate knowledge of the power demand of our datacenter as a time-series $\{P_t\}$, $t \in \{1, ..., T\}$, where T represents our optimization horizon. We denote as P_{max} the maximum of this time-series, which is important to capture for tariffs under which this value affects the utility bill (see below).

Utility Tariffs: Utilities base their tariffs on the actual energy consumption (say a \$/kWh), and the need to sustain the maximum power draw across all their customers within the constraints of their existing capacity. To address the latter concern, utilities dis-incentivize high power draws (especially simultaneously from multiple customers) by two mechanisms: (i) vary a (say as $a(t)$) based on the time-of-day [9]; and/or (ii) track the peak draw (typically averaged over 15 minute windows) and impose a cost of b \$/kW/month (e.g., as in [13]). Our framework is generic enough to accommodate either, and we simply use mechanism (ii) in our discussions/evaluations. Consequently, we need to track P_{max} and calculate the associated b \$/watt/month cost.

Power Sources: In addition to the utility provider, our datacenter can provision renewable generators (based on solar panels and/or wind turbines) both on-site and off-site. The power supply properties for these renewable sources at both locations are assumed to be known. We base these on historical renewable power supply traces derived from NREL [30]. and denote these as time-series of capacity factor (CF).

Carbon Offsetting Requirement: We consider a carbon offsetting target λ for the datacenter, which denotes the percentage of the original carbon emission resulting from the datacenter's operation (specifically, from the generation/transmission of the power it consumes) that we would like to reduce/offset.

Table III summarizes the inputs to our framework.

Input	Symbol	Description
Time Horizon	δt	The time length of one time slot
	T	Total number of time slots
	T'	Number of time slots for wheeling cycle of off-site renewable
Traces	P_t	Power demand (kW) at time $t \in \{1, ..., T\}$
	$CF^l_{n,t}$	Capacity factor of n^{th} renewable source at location l, at time t, $n \in \{wind, solar\}$, $l \in$ {on-site, off-site}
Utility Tariff	a_t	Utility unit electricity price (\$/kWh) at time t
	b	Utility unit peak power price (\$/kW/month)
	C^{bb}_t	Unit power buy-back price (\$/kWh) at time t
Energy Cost	C^{renew}_n	The n^{th} explicit renewable unit capacity cost (\$/kW) including both amortized cap-ex and op-ex
	C^{market}_r	The r^{th} implicit renewable unit energy price (\$/kWh) $r \in \{REC, PPA\}$
	ω	Off-site renewable wheeling charge in terms of the percentage of total energy generated
	C^{dg}	Unit energy op-ex cost (\$/kWh) of DG
	C^{ESD}	ESD cost in unit energy capacity (\$/kWh)
Carbon	λ	Carbon offsetting target

TABLE III
DESCRIPTION OF INPUTS.

B. Optimization Problem Formulation

Decision Variables: Table IV lists all decision variables. Given that our provisioning is intimately tied to certain control actions (e.g., how would a renewable generator's power be actually used? how would ESD be used to bridge the temporal mismatch between the on-site renewable supply and datacenter needs?), we choose decision variables that capture how various sources (explicit or implicit) and ESDs would be used as well as their sizing and location.

	Variable	Description
Renewable Capacity	Z^{on}_i	Max. rated power (kW) of i^{th} on-site renewable source
	Z^{off}_i	Max. rated power (kW) of the i^{th} off-site renewable source
Power Source at time t	P^{on}_t	Power drawn (kW) from on-site renewable sources
	P^{off}_t	Power drawn (kW) from off-site renewable sources
	P^{util}_t	Power drawn (kW) from utility
	P^{dg}_t	Power drawn (kW) from on-site DG
	$P^{market}_{r,t}$	Power drawn (kW) from the r^{th} implicit renewable source
ESD	Y	Energy capacity (kWh) of ESD
	D_t	Discharge rate (kW) of ESD at time t
	R_t	Re-charge rate (kW) of ESD at time t
Peak Realization	P^{grid}_{peak}	Realized peak power (kW) drawn from grid

TABLE IV
DESCRIPTION OF DECISION VARIABLES.

The Objective Function: Our overall objective function is composed of several components. Since these components represent costs that are incurred at different time granularities, we normalize them all with respect to our optimization horizon T. Table V explains each of these components. Putting all these components together, we have our objective as:
Minimize (UtilityBill + OnSiteCost + OffSiteCost + MarketCost + ESDCost + DGOpEx).

Component	Expression	Description
UtilityBill	bP^{grid}_{peak}	Peak cost
	$\sum_{t=1}^{T} a_t P^{util}_t \delta t$	Energy cost
OnSiteCost	$\sum_{n=1}^{N} Z^{on}_n C^{renew}_n$	On-site renewable cap-ex and op-ex
	$-C^{bb}_t \sum_{t=1}^{T} (\sum_{n=1}^{N} CF^{on}_{n,t} Z^{on}_n - P^{on}_t) \delta t$	On-site sell-back revenue
OffSiteCost	$\sum_{n=1}^{N} Z^{off}_n C^{renew}_n$	Off-site renewable cap-ex and op-ex
	$-C^{bb}_t \sum_{t=1}^{T} (\sum_{n=1}^{N} CF^{off}_{n,t} Z^{off}_n - \frac{P^{off}_t}{1-\omega}) \delta t$	Off-site sell-back revenue
MarketCost	$\sum_{t=1}^{T} \sum_{r=1}^{R} C^{market}_{r,t} P^{market}_{r,t} \delta t$	REC/PPA cost
ESDCost	$C^{ESD} Y$	On-site ESD cost
DGOpEx	$\sum_{t=1}^{T} C^{dg} P^{dg}_t \delta t$	DG operational cost

TABLE V
DESCRIPTION OF OBJECTIVE FUNCTION COMPONENTS.

Constraints: The realized peak power drawn from grid P^{grid}_{peak} is a result of workload power demand, ESDs peak shaving, on-site renewable source supply and DG power supply. Meanwhile, P^{grid}_{peak} is lower than the maximum of the time-series P_{max}. This gives us:

$$0 \le P^{grid}_{peak} \le P_{max}. (1a)$$

$$P_t - D_t + \frac{R_t}{\eta} - P^{on}_t - P^{dg}_t \le P^{grid}_{peak}, \forall t. (1b)$$

where D_t and R_t denote discharge and charge rate of ESD, respectively. η is energy efficiency of ESD.

During any time slot t, the datacenter's power needs are supplied by ESD and the mix of the power sources we have considered:

$$P_t = D_t - \frac{R_t}{\eta} + P_t^{on} + P_t^{dg} + P_t^{util} + P_t^{off} + \sum_{r=1}^{R} P_{r,t}^{market}, \forall t. (2)$$

For on-site renewable generation, the amount of power that can be drawn by datacenter at time t is bounded by the power generated at time t. We assume the size of on-site renewable facility is bounded by a factor of γ_1 of the datacenter's maximum power demand. To capture these we have:

$$0 \leq P_t^{on} \leq \sum_{n=1}^{N} CF_{n,t}^{on} Z_n^{on}, \forall t. (3a)$$

$$0 \leq Z_n^{on} \leq \gamma_1 P_{max}, \forall n \in \{1, ..., N\}. (3b)$$

For off-site renewable generation, the amount of energy that can be drawn by the datacenter in a wheeling cycle T' is bounded by the total energy generated minus wheeling charge. Similarly, the size of off-site renewable facility is bounded by a factor of γ_2 of the datacenter's maximum power demand.

$$0 \leq \sum_{t=1}^{mT'} P_t^{off} \delta t \leq \sum_{t=1}^{mT'} \sum_{n=1}^{N} CF_{n,t}^{off} Z_n^{off} (1-\omega) \delta t,$$

$$\forall m \in \{1 \ldots \frac{T}{T'}\}. (3c)$$

$$0 \leq Z_n^{off} \leq \gamma_2 P_{max}, \forall n \in \{1, ..., N\}. (3d)$$

To capture carbon reduction of renewable power sources, we have:

$$\sum_{t=1}^{T} \epsilon^{util} P_t \delta t - \sum_{t=1}^{T} [\epsilon^{util} P_t^{util} + \epsilon^{renew} (P_t^{on} + P_t^{off})$$

$$+ \epsilon^{dg} P_t^{dg} + \sum_{r=1}^{R} \epsilon_r^{market} P_{r,t}^{market}] \delta t \geq \lambda \sum_{t=1}^{T} \epsilon^{util} P_t \delta t. (4)$$

where ϵ^{util}, ϵ^{renew}, ϵ^{dg} and ϵ_r^{market} represent the carbon emission factor of utility, renewable generation, DG and the r^{th} renewable product from market, respectively.

For ESD related constraints, we have captured restrictions on charge/discharge rates, depth of discharge (DoD), lifetimes, self-discharge behavior, ramp up properties and volume constraints. We do not show them here due to limited space and we refer the readers to our prior work [39] for details.

IV. Evaluation

A. Experiment Setup and Methodology

Datacenter Configurations and Power Demands: Our evaluation considers a 3MW datacenter with power infrastructure described in Section II. We use an op-ex model representative of that charged by Duke Electric [13], which has a monthly peak component charge of \$12/kW/month in addition to the energy usage charge. The op-ex, charged monthly, is normalized for the horizon of our time-series. To study the impact of workload power demands on capacity provisioning, we

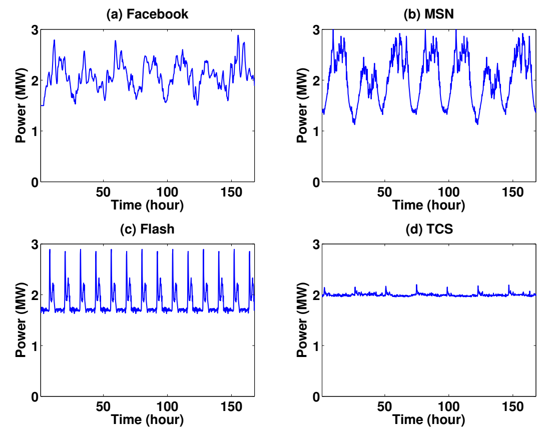

Fig. 2. Datacenter power demands.

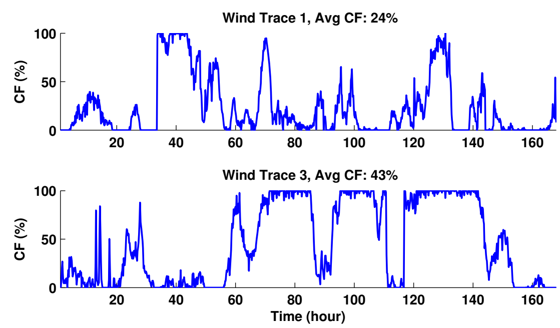

Fig. 3. Wind power capacity factor traces.

evaluate datacenters with real-world power demands reported in recent studies: Facebook [11], MSN [10], streaming media clusters (Flash) [25] and TCS [37] shown in Figure 2. Each power demand time-series spans one week, with each point in the series corresponding to the power needs over a 10 minutes duration (i.e., $\delta t = 10mins$, $T = \frac{1week}{10mins} = 1008$).

We consider three datacenter configurations as our baselines. Our first baseline (denoted as Baseline) is a datacenter sourcing power only from utility. Our second baseline (Base-DG) is a datacenter sourcing power from utility that is also equipped with a diesel generator (DG). Apart from handling power outages (which is the typical role of DG in datacenters today), the DG can also be used to improve op-ex by reducing the peak power needs imposed on the utility. Our third baseline (Base-DG-ESD) is the same as Base-DG except that an ESD is employed for peak shaving in addition to DG as shown in Figure 1. Finally, "ALL" represents our sourcing configuration that is allowed to choose from among all the options - on-site, off-site, and implicit.

	Trace	Energy Potential	Location(ID)	Avg CF(%)
On-site	Wind (W1)	Low	Oregon(25058)	24
	Wind (W2)	Average	Arizona(5129)	30
	Solar (S1)	High	Colorado	22
Off-site	Wind (W3)	High	Colorado(11785)	43
	Solar (S1)	High	Colorado	22

TABLE VI
Wind and solar power traces [20] used in our evaluation.

Renewable Energy Supply: Table II lists relevant parameters for the investment of renewable energy generation facilities.

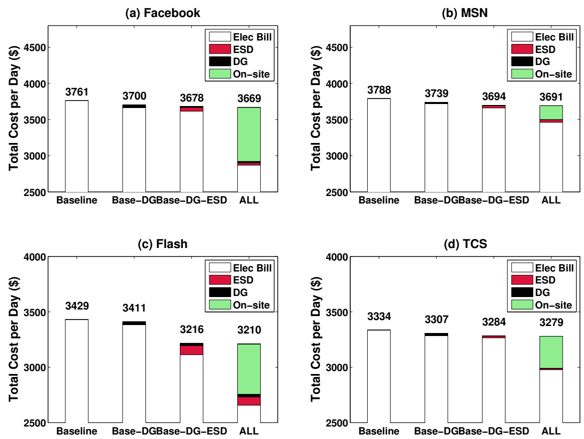

Fig. 4. Daily cost with different datacenter configurations for our 4 power demands. Wheeling charge: 25%, on-site wind CF: 30%, off-site wind CF: 43%, on-site and off-site solar CF: 22% . (Number above bars: cost/day).

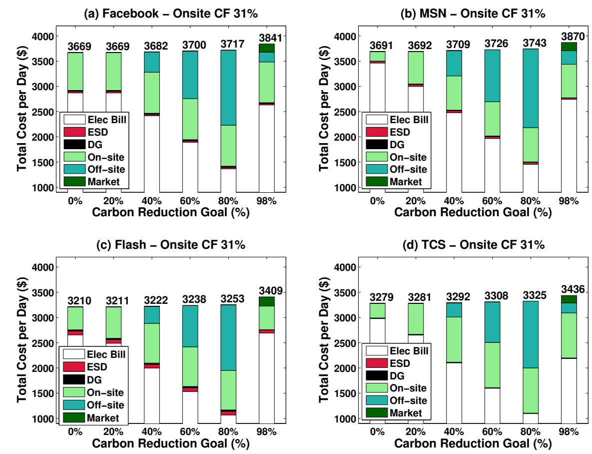

Fig. 5. Costs under different carbon reduction requirements for our 4 power demands. Wheeling charge: 25%, on-site wind CF: 30%, off-site wind CF: 43%, on-site and off-site solar CF: 22% . (Number above bars: cost/day).

We consider renewable power output traces from the Western Wind and Solar Integration Study [20] of NREL that we summarize in Table VI. We choose W3 as our off-site wind trace because it has 43% average generation capacity factor, which is at the higher end of wind energy capacity factor (from 20% to 45%). W1 and W2 are used as on-site wind traces for a sensitivity study of on-site energy potential in Section IV-D, where 24% and 30% represent lower end and average of wind energy capacity factor, respectively, in the U.S. [40]. Figure 3 shows the wind power capacity factor traces of W1 and W3. We use the same solar trace (S1) for both on-site and off-site solar panels, with a relatively optimistic CF of 22% (corresponding to a location in Colorado, U.S.). We choose a wheeling charge of 25% of the total energy generated from off-site renewable, which corresponds to a typical transmission cost of ¢1.5/kWh in the U.S. [29], in all experiments except in Section IV-E. Henceforth, we simply refer to this as a "wheeling charge of 25%." We vary the wheeling charge from 5% to 35% in our evaluation. The wheeling cycle is chosen to be one day (i.e., $T^{'} = \frac{1day}{10mins} = 144$). The prices for the PPA and the REC used in our evaluation are listed in Table I.

B. Datacenter Cost Optimization

We begin by comparing only the cost-saving potential of various sourcing configurations without posing any carbon reduction/offsetting targets on the datacenter. In particular, we seek to understand if various renewable options offer cost-efficacy in the following sense: do the cost savings offered outweigh the costs they add? An affirmative answer would suggest that their role goes beyond merely meeting carbon targets, and they can indeed be used for improving costs. Figure 4 compares the datacenter costs (based on our objective function in Section III) for our three baselines with "ALL", where by "ALL" we denote the configuration where all sourcing options in Figure 1 are considered. We also show the breakdown of these costs into their various components introduced in Section III.

We make several important observations. First, ESD and DG help reduce costs, which implies they must be getting used for reducing the peak draw of the datacenter from the utility (since the unit energy price of both is higher than that of the utility the savings must be due to improvements in peak-related component of costs). Second, demands with different peak properties (height, width, frequency) experience different cost savings (e.g., relative to Baseline, Base-DG-ESD offers higher savings for Flash with high and narrow peaks than for TCS with low and narrow peaks.) Third, "ALL" achieves the best cost for all workloads by sourcing power from a mix of on-site wind, DG, ESD, and utility. We find that solar (on-site or off-site) turns out to be less cost-effective than wind (in fact, this turns out to be the case for the remainder of our evaluation as well). The unit cost of on-site wind is ¢5.1/kWh at 30% CF, and off-site wind costs ¢5.2/kWh at 43% CF including 25% wheeling fee. This high wheeling fee dominates the better CF of off-site wind, with the result that off-site is not a cost-effective option in this case. Another factor in favor of on-site renewable is that it offers reduction in peak power drawn from the utility similar to that offered by DG and ESD. This op-ex peak saving makes sourcing from on-site worthwhile even when its energy price is slightly more expensive than the utility price of ¢5.0/kWh. In fact, given that renewable energy price is higher than the utility price, all cost savings come from op-ex saving via peak reduction. Finally, none of the implicit options (RECs or PPAs) were used because of their higher costs than the utility. In subsequent sections where we introduce carbon reduction requirements, we will see that these options start becoming useful.

Key Insights: (i) On-site renewables can help reduce peak power drawn and hence lower overall costs. (ii) On-site renewables can supplement/replace ESD and DG in their role in peak reduction but at a lower cost.

C. Impact of Carbon Footprint

In this section, we study the impact of different carbon reduction requirements on provisioning decisions. Figure 5 presents the daily costs (along with breakdowns of these costs) offered by "ALL" for our 4 workloads as carbon reduction requirement increases from 0% to 98%. We observe the following interesting trends: (i) increasing carbon reduction requirement results in hybrid renewable solutions, (ii) the capacity of on-site renewable energy stays roughly the same beyond a certain carbon reduction requirement (about 20%), (iii) the capacity of off-site renewable increases with carbon reduction requirement, except for very high carbon reduction (e.g., 98%), and (iv) the total cost increases with higher reduction goals, *but at a very slow rate*.

Comparing with Figure 4, we find that the total cost offered by "ALL" is, in fact, less than the total cost of Base-DG-ESD for relatively low carbon reduction targets of less than 20%. This, along with observation (iv) above, suggests that on-site/off-site renewables might offer effective carbon reduction capability at low costs (or sometimes with cost savings) - *this bodes very well for the environmental-friendly operation of datacenters!*

Let us now try to understand (ii) and (iii) more carefully. The banking facility provided by the grid to an off-site source effectively renders it an "always-on" source, unlike the intermittent on-site renewable, whose output may not be matched with the power needs of the datacenter despite the on-site ESD bridging some of this mismatch. For this reason, whereas on-site was found to be more cost-effective in the last section (with no carbon reduction needs), a hybrid solution of on-site and off-site is found to be more cost-effective with increasing carbon reduction requirements. Essentially, as the carbon reduction target increases, an increasing off-site renewable capacity is provisioned, while a "base" on-site renewable capacity is always provisioned for the peak reduction benefits it offers.

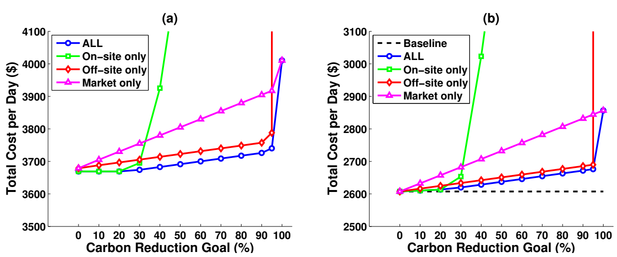

Fig. 6. Cost vs. Carbon reduction for Facebook workload. (a) Total cost including peak opex; (b) Total cost not including peak opex. Wheeling charge: 25%, on-site wind CF: 30%, off-site wind CF: 43%, on-site and off-site solar CF: 22%.

To further understand why a hybrid power sourcing strategy is suggested by our framework, we compare "ALL" with "On-site only" (Base-DG-ESD configuration + on-site renewable generation), "Off-site only" (Base-DG-ESD configuration + off-site renewable generation), and "Market only" (Base-DG-ESD + buying RECs from open market) options. Figure 6(a) shows this comparison for the Facebook power demand (other power demands have similar results and we omit them here). First, "On-site only" costs the least for carbon reduction of less than 30%; "Off-site only" becomes the most cost-effective approach when the carbon reduction goal is greater than 30% but below 95% (explicit options - on-site or off-site - are unable to achieve higher than 95% carbon reduction goal due to their carbon emission factor); for very high carbon reduction region (greater than 95%), we must resort to "Market only" solutions. Second, as the carbon reduction goal increases, the cost of "Market only" increases relatively slowly upto 95% carbon reduction goal. When the carbon reduction goal is very high (above 95%), the use of DG and ESD is reduced for peak shaving due to carbon constraints and hence the total cost increases much faster. Off-site cost shows a similar trend. On-site exhibits a more complicated growth trend (several cost growth slopes) due to the different "balance of power" between peak shaving capability (cost-effective region), intermittency of on-site renewable, and the expensive cost of using ESD to reduce the intermittency (less cost-effective region). "ALL" achieves the lowest cost by sourcing a combination of all three options in different carbon reduction regions based on their cost-effectiveness.

To even further understand the cost savings of employing renewable sources, we remove opex peak cost from the total cost in Figure 6(b) as compared to Figure 6a (total cost includes everything). In Figure 6a, the most cost-effective baseline configuration (Base-DG-ESD) costs more than "On-site only" and "ALL" when carbon reduction goal is less than 20%. However, all the baseline configurations (Baseline, Base-DG, Base-DG-ESD) have the same cost as represented by the dotted line in Figure 6b, and all renewable options including "ALL" cost more than baselines.

This implies that, with the given renewable parameter values, all the cost saving from renewables are due to peak shaving from on-site renewable generation.

Finally, it is also important to note that both on-site and off-site renewable generators have lifecycle emission factors (Table II), which cannot be ignored when meeting carbon reduction requirement as high as 98%. This is the region where renewable electricity from market (with zero emission factor) is bought to meet the high carbon reduction target.

Key Insights: (i) Renewable penetration in the datacenter can go beyond meeting carbon offsetting targets and can even lowering costs. (ii) On-site renewables can reduce op-ex via peak shaving and hence reduce costs. (iii) The most cost-effective options for carbon reduction varies significantly depending on how much carbon reduction is desired, and covers an entire gamut of combinations of different renewable options. (iv) Since the desirable renewable choices for a large range of carbon offsetting targets are off-site sources and market-based options, the need for "supply-following" solutions (where the datacenter's workload has to be modulated to match the renewable generation process) may be more limited and restricted than is assumed in several recent research threads [6], [18], [27], [26], [23].

D. Impact of Renewable Generation Capacity Factor

To understand how renewable source CF affects capacity planning, we do experiments using weaker on-site wind trace (24% CF) than that used in previous experiments (30% CF). Figure 7 shows results for our 4 power demands. Compared

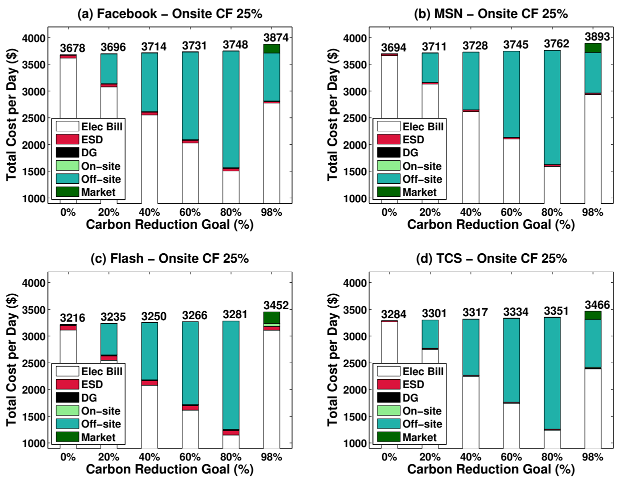

Fig. 7. The impact of on-site renewable generation capacity factor for 4 power demands with on-site wind CF: 24%, off-site wind CF: 43%, on-site and off-site solar CF: 22% . (Number above bars: cost/day)

with Figure 5, we observe that: (i) total costs increase for all cases, (ii) on-site renewable generation is not employed at all. In the 30% CF case, on-site unit electricity cost is ¢5.1/kWh, competitive with utility energy (¢5.0/kWh). Cheaper on-site renewable unit price leads to higher cost savings and larger on-site renewable capacity. On the other end, 24% CF wind trace makes on-site renewable unit electricity costs equal to ¢5.8/kWh, which turns out to be too expensive to deploy compared to off-site with CF 43% with wheeling charge 25% (¢5.2/kWh).

Key Insights: (i) Capacity factor plays a crucial role in selecting the renewable power sources as well as their location. (ii) On-site renewable becomes less cost-effective than off-site renewable when its capacity factor is less than 24% even without any carbon requirements.

E. Impact of Renewable Energy Price

We evaluate the impact of renewable energy price on decision-making by varying the wheeling charge. By varying wheeling charge, we not only capture policies in different regions and countries but also indirectly capture the likely effects of variations in banking fees, ESD cost, and transmission and distribution losses for off-site renewable generation. Figure 8 shows the cost and its breakdown under various wheeling charges (from 5% to 35%) for two different carbon reduction goals (none and 50%). When wheeling charge is less than or equal to 15%, the cost of off-site renewable accounts for a major percentage of total cost. The unit cost of off-site wind with 43% CF is ¢4.6/kWh when 15% wheeling fee is charged (¢4.1/kWh with 5% wheeling charge). This means off-site wind becomes the most cost-effective energy source (even cheaper than utility electricity price which we assume it as ¢5.0/kWh). Note that the electricity bill consists of only opex peak cost (no opex energy cost due to the replacement of sourcing from off-site wind) in Figure 8 when wheeling charge is 5% and 15%. With the low wheeling charge, the total cost by employing off-site renewable becomes

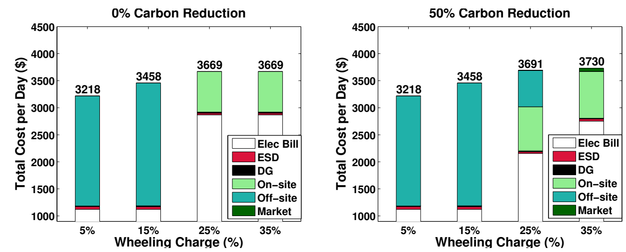

Fig. 8. The impact of off-site renewable energy wheeling charge for the Facebook workload. On-site wind CF: 30%, off-site wind CF: 43%, on-site and off-site solar CF: 22%.

less than that of Base-DG-ESD (see Figure 4). As the wheeling charge increases, sourcing from off-site wind is reduced and is supplemented/replaced by on-site wind and utility power.

Key Insights: (i) Wheeling charge can play a crucial role in selecting the renewable power sources. (ii) Off-site wind penetration can go beyond helping lower carbon footprint - it can, in fact, even lower costs if the CF is adequate and the wheeling charge is reasonably friendly (e.g., similar to that found in Tamilnadu, India [36]).

V. Related Work

There have been related efforts on increasing renewable energy utilization and reducing carbon footprints for data centers on the following topics:

Renewable energy capacity planning: ReRack [8] proposed an extensive optimization-based framework to evaluate the cost of datacenter operation using on-site renewable energy sources. [17] presented a simulator to evaluate datacenter performance and cost effectiveness by applying different on-site renewable capacity planning designs. In contrast to existing work, this paper explores the benefits of all renewable energy choices, and comes up with the best energy sourcing strategy to achieve specified carbon reduction goal.

Renewable and carbon aware workload scheduling: (i) Single datacenter workload scheduling: [34] proposed an approach to manage green energy consumption through server power state scheduling. [6], [18] proposed an adaptive workload scheduler that utilize solar or wind prediction information. SolarCore [27] maximized the utilization of solar energy by using a multi-core power management technique. [26] addressed the intermittency problem of renewable energy by switching workload across two sets of servers in a datacenter - one set powered by renewable energy and another powered by utility grid. (ii) Multi-datacenter geographical workload scheduling: recent work [24], [41], [35] focus on request distribution across multi-datacenter interactive Internet services based on renewable availability and energy cost. [5] maximize the use of renewable energy by workload migration and [28] propose optimization-based framework to study the economic and environmental benefits of renewable energy by geographical load balancing.

VI. Conclusion

We investigated the problem of energy capacity planning for datacenters to achieve specified carbon footprint goals.

We devised an optimization framework to address this problem that can potentially help datacenters achieve their target carbon footprints at minimal cost. We performed extensive empirical evaluation of the key factors that affect energy capacity planning decisions. Our key findings are: (i) not only can renewable penetration in datacenters lower their carbon footprints, it can even lower their costs, (ii) on-site renewables can help lower costs due to their ability to reduce the peak datacenter power draw from the utility, in which case this design can supplement/replace the use of more expensive ESDs that try to do the same, (iii) the most cost-effective options for carbon reduction vary depending on carbon footprint targets - a relatively low goal (upto 30%) is best met using on-site generation, a more carbon reduction goal requires off-site generation, and a (nearly) zero carbon target must resort to renewable energy products such as RECs. A hybrid of these options is the most cost-effective across the spectrum. Our work also suggests that the need for (and extent of) supply-following solutions in green datacenters may be limited. We believe that this paper provides a valuable tool and insights toward right-sizing the energy capacity for more sustainable, green-energy-powered datacenters.

Acknowledgments

We would like to thank Dr. Seth Blumsack, Dr. Susan Stewart and Dr. Jeffrey Brownson for helping us understand renewable energy, policies, and electricity markets. We would like to thank the anonymous reviewers whose comments help us improve the quality of this paper. This work was supported, in part, by NSF grants CNS-0720456, CNS-0615097, CAREER award 0953541, and research awards from Google and HP.

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