Evaluating Energy Storage for a Multitude of Uses in the Datacenter

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Abstract—Datacenters often are a power utility's largest consumers, and are expected to participate in several power management scenarios with diverse characteristics in which Energy Storage Devices (ESDs) are expected to play important roles. Different ESD technologies exist, including little explored technologies such as flow batteries, that offer different performance characteristics in cost, size, and environmental impact. While prior works in datacenter ESD literature have considered one of usage aspect, technology, performance metric (typically cost), the whole three-dimensional space is little explored. Towards understanding this design space, this paper presents first such study towards joint characterization of ESD usages based on their provisioning and operating demands, under ideal and realistic ESD technologies, and quantify their impact on datacenter performance. We expect our work can help datacenter operators to characterize this three-dimensional space in a systematic manner, and make design decisions targeted towards cost-effective and environmental impact aware datacenter energy management.

I. INTRODUCTION

The cost, scalability and environmental concerns posed by the power consumption of datacenters is drawing increasing scrutiny [1]. Each datacenter, houses hundreds of thousands of servers, consumes multi-megawatts of power, and expends millions of dollars in electricity bills. A datacenter's scalability is also limited by the provisioned power infrastructure, where each provisioned watt has been estimated to cost between $10-$25, even if that watt is not consumed [2–5]. Datacenters, often being a utility's major customer, play an important role in the peak power draw, which can imply broader environmental consequences of needing to augment the supply with more polluting sources during high demand periods. The instantaneous power draw, and its consequent energy aggregate over time, are thus equally important for each datacenter. While much has been done on both hardware and software sides, as well as in power distribution and cooling system optimizations for addressing this problem, it is only recently that the importance of energy storage for the datacenter has gained attention [4–6]. Even these studies have focused on a single energy storage technology, and/or a single/limited possible usage in the datacenter, and/or only looked at a subset of the cost-benefit trade-offs. This paper presents a broader framework to examine all these issues for a wide spectrum of energy storage technologies, and presents both cost, real-estate, as well as environmental metrics when each is employed to address its different possible usages in the datacenter.

In production datacenters, to date, Energy Storage Devices (ESDs) have only been employed as a Power Backup (PB) mechanism, to take on the datacenter load upon an outage, until either the power comes back up, or the Diesel Generators kick in. In addition to PB, there are several other important power modulation demands in a datacenter: (i) Peak Shaving (PS) - where the goal is to cap the peak within a certain value (either to the outside world for peak reduction on the grid, or within the provisioned power infrastructure of the datacenter); (ii) Power Regulation (PR) - where, being a utility's major customer, the datacenter can actively participate in power markets such as power regulation services for a smarter grid [7]; and (iii) Renewable Integration (RI) - with the increasing public attention, datacenters are increasingly looking to source from on-site renewables [8–10], making them more susceptible to the vagaries of generation capacities.

Recognizing these needs, recent research has looked to employ ESDs for each of these purposes, apart from the traditional PB usage. With the temporal power demand shifting capabilities, an ESD can charge during periods of low demand or high supply (whether from the grid or from on-site renewables), and be the source of power during high-demand/low-supply periods to serve all these 3 usages (PS, PR and RI). Consequently, there have been research studies looking to curtail the peak demand [4, 11], participation in PR services [12, 13], and boosting renewable integration [14, 15] with ESDs in the datacenter. However, all these works have typically looked at (i) one ESD technology, and/or (ii) one aspect/usage (PB/PS/PR/RI), and/or (iii) one metric of interest (usually cost or availability). There are, however, a multitude of ESD technologies each with its own idiosyncrasies, making it unclear if one technology is universally the best across the diversity of usages. With each usage posing different requirements, what may be good for one may not necessarily be good for another. For instance, consider PB, where the ESD has to take on the full datacenter power needs, albeit for a short time - the power demands on the ESD are much higher than the energy needs. On the other hand, mechanisms like PS, may demand more energy, and not as taxing on the power front. ESDs are very diverse in terms of their effectiveness on providing power vs. energy, (e.g. ultracapacitors/flywheels are good for the former while compressed air is better for the latter). Unfortunately, many popular electrochemical batteries including Lead-Acid (LA) and Lithium-Ion (LI), couple the power and energy capacities, i.e. providing for one automatically determines the capacity of the other, making them less suitable for diverse purposes. Further, it is not just about the economics (costs, real-estate, and availability consequences) of power and energy - datacenters are increasingly conscious of their eco/carbon-footprints [8–10]. When using ESDs for the above purposes, including RI, the eco-footprint of the ESD itself should be taken into account - the sustainability of materials used in the ESDs, the carbon footprint of their manufacturing and operation, the toxicity of the materials upon end-of-life. To our knowledge, no prior study on ESDs in the datacenter has investigated these issues, and the impact of the intended usage on these issues.

Despite the potentially large market for ESDs in the datacenter, there is a clear void in the understanding of this 3-dimensional space - *ESD Technology × ESD Usage × ESD Cost and Environmental impact* - that this paper intends to fill. Understanding this space can help answer several questions: what kinds of ESDs should be provisioned in the datacenter for different purposes? should we consider 1 solution for all purposes? does cost-effectiveness also translate to the most "green" option(s)? does the ecological benefits provided by the ESDs for a datacenter to source from greener sources offset the footprint of the manufacturing, subsequent operation and disposal of the ESD itself? These are just some of the preliminary issues that we intend to study.

While one could argue that studying ESDs for a datacenter may be no different than that being studied in other domains, say transportation which is the largest in terms of ESD market today [16]. Datacenters offer a unique set of opportunities and challenges that warrant such a domain-specific study: they are stationary and not mobile (with weight and space not as much a concern here), operationally quite different in the demand modulation knobs that are available (server consolidation, DVFS, etc.), and ESD usage is to take on all or part of the supply load rather than as an ignition (normal vehicles) or efficiency improvement mechanism (hybrid vehicles).

In this paper, we extensively evaluate this 3-dimensional space for ESDs in the datacenter:

- We consider multiple ESD technologies, from non-electrochemical technologies such as Compressed Air and Flywheels, to two important (and currently prevalent) electrochemical ESDs (Lead-Acid and Lithium-Ion). We also consider emerging technologies such as flow batteries[1] [17–19]. We characterize these technologies in terms of their energy and power densities (coupled in some cases), costs, volume, efficiencies, charge/discharge characteristics, lifetime issues, carbon footprint, etc.
- We consider the diversity of datacenter ESD usages (PB, PS, PR and RI), for each of these ESDs, and their intrinsic characteristics impacting their usage (high power versus energy needs or vice-versa, ability to retain charge, ramp times to discharge, usage frequency, etc.).
- We consider ESD performance metrics of costs, real-estate needs and ecological footprint on both procurement/manufacturing (capital) and operating fronts. Each ESD has long term benefits over its lifetime in terms of reducing power provisioning and operational energy cost from demand response, as well as in avoiding/reducing the use of less green energy. However, these benefits have to be weighed against ESD procurement costs, and their eco-footprint from manufacturing and operating them in the first place. With many ESD electrochemistries having harmful chemicals and/or relatively scarce materials, their procurement and operating costs and environmental foot-

print are very important design considerations. Hence, we quantify the performance of datacenter ESD usage not only based on cost and real-estate needs, but also based on carbon emissions, one of the key indicators of environmental impact [20].

To conduct this study, we use several real production datacenter traces. We compose an optimization problem that considers the different intended usages for each ESD, parameterized by their inherent and operating characteristics. We run the optimization using published values for these parameters from prior literature, and compare the cost and eco-footprint. Here are some salient findings from this study:
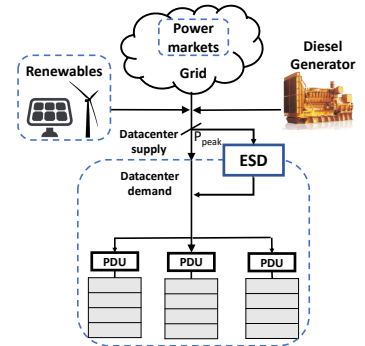
- The demands of emerging usages (PS, PR and RI) for ESDs are very different from that of traditional backup - peak shaving requires high energy capacity; power regulation requires frequent charge and discharge operations; renewable integration requires larger and longer storage.
- Conventional electrochemical ESDs such as Lead-Acid and Lithium Ion (traditionally used for PB) are limited by their coupled power-energy properties, making them less suited for energy demanding PS and RI.
- If we need to use one ESD technology across all possible usages, then flow batteries are the most cost-effective, incurring $37\% - 45\%$ less cost than the next best alternative.
- Our analysis also indicate that, in addition to cost benefits, flow batteries offer attractive carbon reductions compared to other ESDs (except Compressed Air) for integration of low carbon sources. However, their poor energy efficiency makes them less suited in the presence of high carbon sources.
- This joint characterization has helped us to identify the emerging flow battery technology as providing the right trade-offs across a multitude of usages in the datacenter. They provide this by leveraging the benefits of electrochemical ESDs for fast response and placement flexibility, while allowing independent power and energy sizing, unlike Lead-Acid or Lithium-Ion. Beyond cost benefits, flow battery also allows for a much more eco-friendly footprint, as their raw materials are derived from abundant and greener sources.

II. BACKGROUND

Datacenter power hierarchy: Figure 1 presents a simplified view of power flow in datacenters (DCs). In a typical datacenter, power utilities serve as the primary power source and Diesel Generators (DG) as the backup power source. In emerging datacenters, an on-site generation source could replace the power utility and the backup DG [21]. The power demand of a datacenter consists of the IT server load and the cooling power load. Power from the supply side is delivered to the end servers using

Fig. 1: Datacenter power hierarchy. Emerging ESD usages are marked in dotted lines.

a hierarchy of power infrastructure comprising of power

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[1]Flow batteries have been prototyped since 1980s, and their traditional versions require very high capital costs. As a result, flow batteries have been little explored in the context of these emerging power management scenarios studied in this work, especially for datacenter usage. Only recently, significant advances have been made in the material selection enabling cost-reduction resulting in widespread applicability of such ESDs, warranting a fresher look at these ESDs. Interested readers could refer to [17] for detailed information on recent advances in flow batteries leading to the development of low cost and green electrolytes.

supply/distribution elements and ESDs. ESDs act as buffers between the power supply and demand elements, to perform power conditioning and backup services. These ESDs are either placed centrally at the DC level or distributed at different levels within a datacenter (clusters/racks/servers) [11, 22, 23].

ESDs for power backup: Datacenters are designed to be highly available. To avoid downtime due to utility power outages, datacenters employ ESDs and Diesel Generators. Upon a power outage, complete transition of datacenter load to DG would incur a non-negligible transition delay (in the order of seconds to minutes), during which ESDs in the Uninterrupted Power Supplies (UPSs) sustain the DC load. Such ESDs are seldom used because of infrequent power outages [24]. However, during their usages, they require high power capacity (to handle the entire DC load) and low energy capacity (to sustain short transition times). Lead-Acid is the most common technology found in datacenter UPSs, as its properties complement the needs of power backup scenarios.

III. ENERGY STORAGE IN DATACENTERS

A. Emerging ESD usages

Datacenters can employ ESDs for various emerging power demand or/and supply management scenarios as follows:

Peak Shaving (PS): On the demand side, ESDs could be used to perform demand response to reduce operating and capital expenditures [4, 6]. Peak shaving is an instance of demand-response, wherein power load over a peak threshold is suppressed using ESDs. It helps datacenter to reduce the peak power costs of its monthly electricity bill. In addition, it helps datacenter to under-provision its power infrastructure, and saves substantially on the capital expenditure. The power and energy capacity required for this usage would depend on the peak shaving threshold. Unlike power backup, the operational frequency in this case would be high.

Power Regulation (PR): On the supply side, ESDs could enable a datacenter to actively participate in power markets [12, 13]. Power Regulation is a representative of datacenter′s participation in emerging power markets for cost benefits. Regulation services are invoked to balance variability in grid load. A datacenter can subscribe to a certain power capacity to act as a regulation reserve. According to the market regulation signal, all or part of the subscribed capacity is injected into (or withdrawn from) the grid. ESDs can be used to serve this signal without impacting the IT load of datacenters. The signal varies rapidly (in the order of seconds), demanding frequent usage. So, participation in PR would require high power capacity, low energy capacity, and frequent charge-discharge cycles from the energy storage devices.

Renewable Integration (RI): In the presence of on-site power generation, a datacenter could employ ESDs to smooth out variations between supply availability [14, 15] and demand fluctuations [21]. Thus, the energy storage needs are determined by both the power source′s generation profile and the datacenter′s demand profile. Unlike other usages, the ESDs used in renewable integration require a high power capacity and also a very high energy capacity (spanning the energy needs of several days). In addition, during the periods of low generation, ESDs may also have to wait without recharging for long periods until the generation output becomes surplus.

Table I captures the salient characteristics of each of these above usage scenarios in comparison with traditional power backup usage. In section VI, we quantify the impact of these characteristics on ESD provisioning and operating needs.

B. ESD Technologies

In addition to the inherent characteristics of usage scenarios, the properties of an ESD technology also impacts the effectiveness in serving the above usages. From the DC operation perspective, metrics such as cost, space requirements, lifetime, energy efficiency, etc. are directly important. However, note that large energy storage requirements such as that of datacenters place a corresponding increase in material demand. And, materials used in the ESD technology determine the cost/carbon expended in manufacturing the ESD, its operational safety and also its end-of-life disposal/recycling overheads.

Many ESD technologies exist, including emerging green alternatives such as flow battery, and they offer contrasting properties across different metrics of performance. These technologies include the following:

- **Electrochemical ESDs** are the most popular owing to their flexibility, scalability and technological maturity. Electrochemical Lead-Acid (LA) batteries are commonly seen in datacenter UPSs. They are a low-cost and a mature technology. On the downside, LA batteries have a shorter lifetime and poor energy density. In recent days, Lithium-Ion (LI) is also widely adopted for datacenter energy storage [25]. LI batteries have high power and energy density making them attractive for deployment close to the servers [23]. They also provide high efficiency and longer life compared to LA, but at a higher cost. Both LA and LI have material related disadvantages. Lead is a hazardous material and at the end-of-its-life, proper care needs to be taken to recycle or dispose of the ESDs. LI batteries depend on two elements, viz., Lithium and Cobalt, both of which are limited in their natural availability [26, 27].
- **Ultra-capacitors (UC)** are electrostatic energy storage devices, made of electrochemical materials. They can sustain very high power demand for very short periods at high efficiency. However, their energy cost is very high, prohibiting them for usages that require a substantial runtime. UCs also use electrochemical materials and thus have similar material related disadvantages as LA and LI.
- **Compressed Air Energy Storage (CAES)** is a thermodynamic ESD to store energy in the form of pressurized air, which is later used to run turbines to generate electricity. CAES provides very high energy capacity, and can sustain longer hours of power delivery. However, it requires a large space and also has slow ramping properties. CAES may not be suitable for all DCs, as it is constrained by site-suitability issues (e.g. reliance on geological structures) [28].
- **Flywheels (FWs)** are mechanical energy storage devices that use rotor momentum to store energy. FWs have high power density and are highly effective for short-term storage. But, they have low energy density, and their efficiency reduces drastically with longer storage time, making them ineffective for a long-duration energy storage.
- **Flow battery (FB)** is an emerging ESD technology that uses a hydraulic subsystem to pump fluid electrolytes through a cell stack, facilitating electrochemical reactions. Flow

Property	Power Backup	Peak shaving	Power Regulation	Renewable Integration
ESD load	DC demand	Shaved DC peaks	Regulation signal	Supply/demand mismatch
Objective	Max. availability	Min. cost	Max. profit	Max. renewable use
Power (W)	High	Low - Medium	High	Low-Medium
Energy (Whr)	Low	Medium -High	Low	Medium-High
Discharge frequency	Rare	Medium-High	High	Medium
Discharge duration	seconds to minutes	minutes to hours	seconds to minutes	hours to days
Recharge availability	Short term	Short-Medium term	Short term	Medium-Long term
Effort	Mandatory	Mandatory/Best-effort	Best-effort	Mandatory/Best-effort

TABLE I: Properties of traditional power backup usage, in contrast with emerging scenarios under evaluation.

Property	Ideal	LA	LI	FW	CAES	FB
Decoupled power and energy?	Yes	No	No	Yes	Yes	Yes
Placement Flexibility	Yes	Yes	Yes	Yes	No	Yes
Specific power(SP in W/Kg)	-	180	300	400	-	-
Specific energy(SE in Wh/Kg)	-	38	182	10	-	-
Discharge/Charge rate (γ)	1	10	5	1	4	1
Efficiency (η)	1.00	0.75	0.85	0.95	0.68	0.75
Self-discharge ($sd_{\delta=day}$ in %)	0	0.3%	0.1%	100%	low	low
Cycle life $\times 1000$ (L_{cycle})	200	2	5	200	15	12
Float life (L_{float} in yrs)	12	4	8	12	12	12
Depth of discharge (dod_{max})	100	80	80	100	100	100
Ramp time (T_{ramp} in seconds)	0	0.001	0.001	0.001	240	0.001
Power costs (in C_p $/KW)	-	125	175	250	600	1000
Energy costs (in C_e $/KWh)	-	200	525	5000	50	250
Energy Density (ED in Wh/L)	-	80	150	80	6	19
Power Density (PD in W/L)	-	-	-	-	-	48.82
Embodied carbon [33–37]	-	86.84	151	222	19.4	89.8
(ϕ_{esd} in Kg CO_2e/KWh-storage)						+160/KW

TABLE II: ESD specific parameters from [11, 19, 38–40].

batteries enable independent sizing of power and energy capacity with separation of cell stack and electrolyte tanks which determine power and energy capacities respectively. This separation also allows for higher depth of discharges without affecting the battery health, and negligible self-discharge during long periods of energy storage. In addition to operational performance, emerging flow battery technologies use low cost and non-toxic electrolytes based on abundant materials [29–31] which can significantly reduce their impact on the environment. Some of these emerging green electrolytes are drop-in replacements [31] for existing flow battery architectures, requiring no additional changes to the existing flow system. However, flow battery's disadvantages include poor energy density, low overall system efficiency ($\approx 75\%$) [32], and high system management complexity (i.e. controlling pump speed and flow rates).

Table II provides the characteristics of the ESD technologies evaluated in this work.

IV. RELATED WORK

Prior work have recognized the importance of ESDs in datacenter power and energy management [4–6, 41–45]. These efforts encompass the following areas of research:

ESD workloads in DCs: Prior works have characterized the power demand profiles of production datacenters [46–48]. Specifically, in the context of ESD usage, [47] analyzes ESD workloads in DCs for peak shaving using the abstractions of peaks and valleys to capture temporal heterogeneity within a single ESD usage scenario. In this work, we characterize the heterogeneity of different emerging ESD usages in DCs, and their impact on ESD provisioning and operation.

ESD technologies for DCs: LA and LI are the most commonly used (and analyzed) ESD technologies in datacenters [4–

6, 25, 49, 50]. Recent works have evaluated the performance of ultracapacitors, flywheels, and compressed air energy storage [11, 12, 44]. As we will show later, our joint characterization helps to identify the insufficiencies of current ESD technologies in meeting emerging DC needs, and helps us make a case for emerging flow batteries in datacenters.

ESD performance in DCs: Prior works on datacenter focus on cost benefits in employing ESDs [5, 6], occasionally in combination with their energy efficiency [44] and volume requirements [11]. While environmental impact of ESDs have been studied in related domains which rely extensively on ESDs [20, 51, 52], it is little understood in the context of datacenters. In this work, we make initial attempts towards quantifying environmental impact of ESDs usages in datacenters based on their carbon emissions.

V. SYSTEM MODEL

The goal of this work is to evaluate the effectiveness of different ESD technologies when used for emerging DC usage scenarios. In this section, we formalize our metrics and models to systematically explore this design space. Table III summarizes the list of symbols used this model.

A. System performance metrics

We evaluate ESDs on the following metrics of performance. These metrics span the manufacturing, provisioning and operating phases of the ESDs' lifetime.

Total cost of ESD ownership (TCO) [$]: Cost is one of the most important metrics that determines ESD selection in datacenters. An ESD's capital cost depends on its unit power and energy capacity costs (C_p, C_e), power/energy capacity requirements (p_{max}, e_{max}), and the rate of replacement (N) as determined by the usage patterns. An ESD's operating cost depends on unit energy cost (α) and energy losses (EL) due to charge/discharge losses and self-discharge properties of the ESD. Total cost of ESD ownership is reported in the units of dollars. TCO = (Battery Provisioning Costs $\times N$) + ($\alpha \times EL$). For ESDs where power and energy are coupled, provisioning cost is the maximum of power provisioning cost ($C_p \times p_{max}$) and energy provisioning cost ($C_e \times e_{max}$). For ESDs with decoupled power and energy capacity, it is the sum of the power and energy provisioning costs.

Volume [Liters]: A datacenter's real-estate cost budget is affected by its location (population centers vs. remote), size (large cores vs. small edges), and packaging design (containerized vs. co-located). Hence, we consider the space required to provision ESDs as a performance metric. The space required for an ESD depends on its provisioned energy capacity (e_{max})

and its volumetric energy density (ED). This metric is reported in the unit of liters. Volume $= \frac{e_{max}}{ED}$. As a flow battery has decoupled power and energy capacity, this metric includes an additional component to represent cell stack volume: $\frac{p_{max}}{PD}$, where PD is the volumetric power density of the flow battery.

Carbon emissions [kg CO_2 equivalent]: One of the main reasons for the emergence of various power management scenarios using ESDs is to reduce the environmental impact of DC energy use, i.e. harmful effects of carbon emissions, either by increasing clean energy penetration or by reducing the use of high carbon sources. Note that, even if the stored energy is derived from a low carbon source, energy intensive ESD production and associated emissions (both fuel use and chemical reactions) could negate the benefits of energy storage. So, we evaluate carbon emissions from both ESD production and operation. Carbon emissions during production is specific to ESD technology, and it scales with provisioned capacity. Carbon emission during operation depend on ESD's operational energy losses and the carbon emission factor of the power source. It is reported in Kg equivalents of CO_2. Carbon emissions $= (\phi_{esd} \times e_{max} \times N) + (EL \times \phi_{supply})$. For flow battery production, carbon emission is computed separately for power and energy capacities. So, carbon emissions of flow batteries include an additional component $(\phi_{pwr} \times p_{max} \times N)$ [37], where ϕ_{pwr} is the emissions per unit power capacity.

An ESD's performance depends on both usage and technology characteristics, and it spans both provisioning and operation stages of the ESD's lifetime. We develop a modeling framework to jointly capture these properties to obtain relevant inputs on ESD provisioning and operation to estimate the performance metrics.

Symbol	Description
T	Simulation duration
t	Time slot index
δ	Time slot duration
D_t	ESD discharge workload
R_t	ESD recharge workload
P_t	Datacenter power demand
P_{cap}	PS - shaving threshold
S_t	PR - grid signal
$\mathcal{C}$	PR - subscribed power
G_t	RI - generation profile
e_t	ESD charge level at t
d_t	ESD discharge power
r_t	ESD recharge power
U_{cycles}	ESD usage cycles per year
L_{dc}	Datacenter lifetime
L_{esd}	ESD lifetime
p_{max}	Provisioned power capacity
e_{max}	Provisioned energy capacity
N	No. of ESD replacements
α	Unit electricity price
ϕ	Normalized CO_2 emissions
EL	Energy losses

TABLE III: Model parameters

B. ESD workload model

Workload model captures the charge and discharge pattern directed by the usage scenario. It identifies the magnitude and duration of the power demand that has to be discharged from (and recharged into) an ESD, over the modeling time horizon $t \in \{1, T\}$. This information is captured in the discharge profile D_t and the recharge profile R_t as described below:

Peak shaving: ESD workload for PS depends on datacenter power profile ($P_t, t \in \{1..T\}$) and the capping threshold P_{cap}. Given these inputs, the discharge and recharge profiles of peak shaving usage is defined as follows: if $P_t > P_{cap}$ then $D_t = P_t - P_{cap}$ and $R_t = 0$; otherwise, $R_t = P_{cap} - P_t$ and $D_t = 0$.

Power regulation: ESD workload for PR follows the regulation signal from the grid, and its magnitude depends on the regulation capacity subscribed by the datacenter. Given a subscribed power capacity $\mathcal{C}$ and the signal for a time slot S_t, the discharge and recharge profiles are modeled as follows: if $S_t > 0$ then $D_t = S_t \times \mathcal{C}$ and $R_t = 0$; otherwise, $R_t = -S_t \times \mathcal{C}$ and $D_t = 0$.

Renewable integration: ESD workload for RI depends on the datacenter demand profile and the power generation profile. ESD workload model captures the mismatch between the datacenter power demand P_t and the power generation output G_t. If $G_t < P_t$, the ESD should discharge $P_t - G_t$. If $G_t > P_t$, ESD could use $G_t - P_t$ for recharging.

These recharge and discharge profiles serve as the inputs to the ESD model.

C. Joint modeling of ESD technology and workload

Given an ESD workload, the actual operation of the ESD would be constrained by the realistic properties of the given ESD technology. We capture such constraints as follows:

At any time t, total useful discharge from the battery should meet the demand specified by the usage scenario D_t. Useful discharge of an ESD is represented as the product of its actual discharge from the stored energy d_t and its round trip energy efficiency η.

$$d_t \times \eta = D_t, \forall t \qquad (1)$$

At any time t, the recharge power of the ESDs r_t is bounded by power available for recharge R_t.

$$r_t \leq R_t, \forall t \qquad (2)$$

The above inequality is applicable only to both PS and RI. For use in PR, the ESDs are expected to closely follow the regulation signal, with an added penalty for any mismatch. To address this, we model equation 2 with a stricter equality constraint for PR.

During any time slot t, the total energy stored in the battery e_t is determined by the stored energy in the previous time-slot e_{t-1} (accounting for self-discharge losses sd_δ) and the difference between the recharged and discharged energy $((r_t - d_t) \times \delta)$.

$$e_t = (1 - sd_\delta) \times e_{t-1} + (r_t - d_t) \times \delta, \forall t \qquad (3)$$

In addition, ESDs are constrained by their maximum depth of discharge: $(1 - dod_{max}) \times e_{max} \leq e_t \leq e_{max}, \forall t$.

Provisioned power capacity of an ESD is jointly determined by the discharge and recharge the ESD undergoes, as well as the ramping properties.

$$d_t \leq p_{max}, r_t \leq \frac{p_{max}}{\gamma}, \forall t \qquad (4)$$

$$\frac{d_t - d_{t-1}}{\delta} \leq \frac{p_{max}}{T_{ramp}}, \forall t \qquad (5)$$

where γ is the ratio of discharge rate to recharge rate of the ESD, and T_{ramp} is its ramp time.

For electrochemical ESDs with coupled power and energy, $p_{max} = e_{max} \times \frac{SP}{SE}$ relates the power and energy capacities. Here, $\frac{SP}{SE}$ represents the ratio of specific power and specific
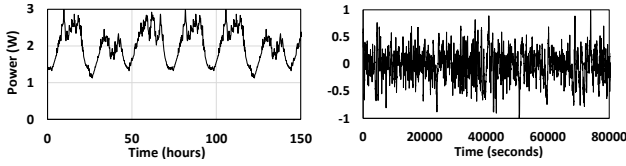
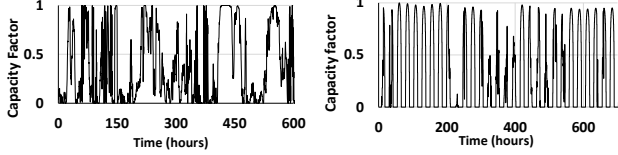Fig. 2: DC power trace

Fig. 3: PJM signal

Fig. 4: Solar generation

Fig. 5: Wind generation

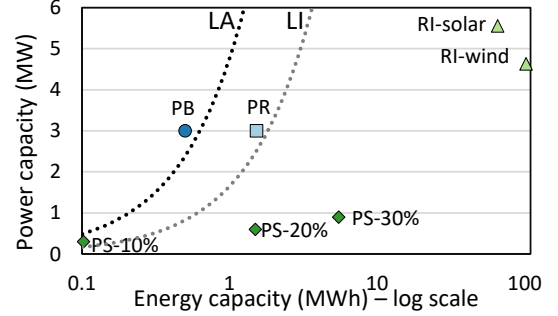| Property	Grid	Solar	Wind
Energy cost (α in \$/KWh)	0.05	0.0742	0.0585
Carbon emissions (ϕ_{supply} in Kg CO_2e/KWh)	0.58	0.053	0.029

TABLE IV: Power supply parameters. Sources: [59, 60]

Fig. 6: Power and energy requirements of ESD usages under an ideal ESD. Dotted lines represent the relationship between provisioned power and energy when LA and LI are used.
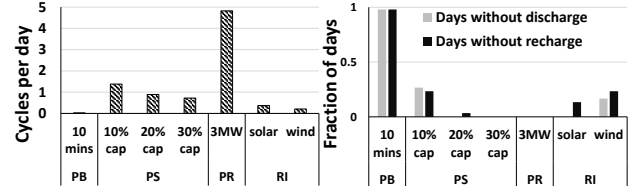

Fig. 7: ESD usage cycles.

Fig. 8: ESD inactivity.

energy of the ESD. It connects available power capacity based on provisioned energy capacity and vice-versa.

We pose this model as an optimization problem with an objective to minimize amortized ESD provisioning and operating costs. The model's outputs are the following metrics on ESD provisioning and operation: (i) rated power capacity (p_{max}), (ii) rated energy capacity (e_{max}), (iii) energy losses ($(1-\eta)\sum d_t + sd_\delta \sum e_t$) and (iv) the number of ESD replacements (N). An ESD's lifetime (L_{esd}) is determined by its float life (L_{float}), rated cycle life (L_{cycle}) and the actual cycles it undergoes ($U_{cycles} = \frac{\sum d_t}{dod_{max} \times e_{max}}$ in cycles per years). So, lifetime of an ESD is given by $L_{esd} = min(L_{float}, \frac{L_{cycles}}{U_{cycles}})$. And, the number of replacements over the lifetime of a datacenter ($N = \frac{L_{dc}}{L_{esd}}$). These metrics serve as inputs to the performance models defined in section V-A.

VI. CHARACTERISTICS OF EMERGING ESD USAGES

We begin by studying the inherent provisioning and operating characteristics of different ESD usages without being influenced by the underlying technology that serves them.

A. Evaluation setup

Our evaluation setup uses a 3 MW datacenter, with a centrally managed energy storage in the power hierarchy as shown in figure 1. We assume the DC infrastructure's lifetime (L_{dc}) to be 12 years [53], and the results are amortized to this period. We assume that this datacenter is served by a single power source at a time. For PS and PR, power grid utility acts as the power source; whereas, for the RI scenario a renewable generation facility powers the datacenter. Table IV lists the operational costs and carbon emissions of these power sources. We use real world datacenter power demand traces from prior studies [46, 54, 55], with msn [54] trace as the baseline. Figure 2 shows the msn power profile for a period of 150 hours, sampled at every 10 minutes.

Peak Shaving: Performance of peak shaving depends on the shaving threshold that determines height, width, and frequency of the peaks. Using the msn trace we evaluate peak shaving for the thresholds of 10%, 20%, 30% of the datacenter's maximum power over a simulation period of 30 days. For the 3 MW datacenter in our study, this translates to peak thresholds of 2.7 MW, 2.4 MW, and 2.1 MW respectively. To compute the

cost savings from peak shaving, we use \$12/KW/month as the peak component of the electricity bill and a capex reduction of \$10 per shaved watt. We report the benefits from peak shaving and the ESD costs separately.

Power Regulation: We use a realistic regulation signal from PJM power market [7], and model the PR operation for 24 hours. Figure 3 shows the normalized signal for this period, which varies once every 2 seconds. We assume that datacenter subscribes 1 MW power for regulation, and receives a market price \$30 per MW of subscribed power per hour, as typically seen in current markets [56].

Renewable Integration: We evaluate RI for two different supply sources: solar and wind with average capacity factors of 27.55% and 41.32% respectively. These supply profiles are obtained from NREL [57, 58] for sites 198298 and 49194 for solar and wind respectively. Figure 4 and 5 present their generation capacity profiles. We assume the datacenter to be powered entirely by this renewable facility. Under this configuration, total energy consumption of the datacenter corresponds to over 68% utilization of the renewable energy output. And, ESDs are employed to meet 50% and 40% of the total DC energy needs for solar integration and wind integration respectively.

B. Power backup vs. Emerging ESD usages

Emerging ESD usages have diverse provisioning needs and operating characteristics, which are different from that of traditional power backup. To understand the magnitude of their differences, we study technology independent properties of these usages using our modeling framework, when serviced by an ideal ESD. An ideal ESD allows independent sizing of

power/energy capacity, incurs no energy losses, provides fast response, lasts longer and can discharge the entire charged capacity without any repercussions. Table II shows the modeling parameters for such an ESD.

Provisioning characteristics: Figure 6 presents the power and the energy capacity requirements of these usages for the above datacenter configuration. Their power capacity requirements range from 330 KW to 5.5 MW ($16\times$ difference). And, their energy capacity requirements range from 100 KWh to 100 MWh ($\approx 1000\times$ difference). Among these usages, peak shaving requires low power capacity (we consider 10%, 20%, 30% of DC peak demand). However, the energy capacity requirements increase from minutes to hours as the shaving threshold increases. Note that, renewable integration requires comparable power capacity to power backup, but requires much higher energy capacity. Power regulation services have similar power vs. energy needs as power backup. However, they differ vastly in their operational front.

Implications: In realistic electrochemical ESDs, power and energy capacities are coupled, as determined by their specific power (W/Kg) and specific energy (Wh/Kg). By provisioning a certain mass of the ESD material, one provisions certain power capacity and certain energy capacity jointly. As a result, provisioning for one dimension automatically provisions the other, impacting the provisioning costs irrespective of the usage requirements. For instance, LI has a specific power of 300 W/kg and a specific energy of 182 Wh/Kg. So, a traditional LI battery with 1 KWh energy capacity comes with 1.6 KW of power capacity, even if the usage scenario does not require that much. In the context of datacenters, figure 6 shows the mismatch between power/energy needs of individual ESD usages vs. the power/energy capacity offered by LA and LI. The two dotted lines represent the available energy capacity (x-axis) for the provisioned power capacity (y-axis) for LA and LI technologies. And, the points represent the requirements of the usage scenario. It shows that LA and LI have power energy sizing close to that of PB. However, for RI and PS (cap=20% and 30%), we see that when LA and LI are sized for the usage specific power needs (y-axis) their energy capacities are an order of magnitude smaller in meeting the usage specific energy needs (x-axis). Consequently, when electrochemical ESDs such as LA and LI are employed for these usage scenarios, their power capacity would be highly over-provisioned resulting in very high power costs.

Operational characteristics: In power backup, ESDs are almost always idle as power outages are rare. And, even after a discharge, these ESDs get a plenty of opportunities to recharge once the power supply is restored. These operational characteristics do not hold anymore for the emerging usages.

Usage frequency: Figure 7 shows the average number of charge-discharge cycles per day for these usages. PR has the highest usage (4.7 cycles per day). PS indicates a daily usage pattern (≈ 1 per day). RI indicates a cycle spanning multiple days (< 1 cycles per day). Note that each of these scenarios require ESDs to undergo higher usage than power backup.

Implications: Realistic ESDs can only undergo a limited number of cycles (see table II) before they wear-out and fail. Using ESDs for these emerging usages may lead to premature failure of the ESDs, and it thus requires careful evaluation.

Recharge availability: Figure 8 shows the fraction of days ESDs are not employed for either recharging or discharging. ESDs are not employed for a small fraction of days when used for PS or RI. The reason for inactivity is similar for power backup and peak shaving. The DC does not require the ESD to discharge, and consequently it does not have to recharge either. However, for RI, reduced (or increased) power generation leads to reduced opportunity to recharge(or discharge).

Implications: Under conditions when recharge availability is low and stored energy has to be retained for a longer period of time, self-discharge properties of the ESDs could impact their long term power availability.

Key Insights: Emerging ESD usages in datacenters are in stark contrast with the traditional power backup in their provisioning needs and operating patterns. When compared to power backup, these usages demand ESDs to undergo frequent cycles and/or require larger energy storage capacity as well. In addition, integrating highly variable power source may limit the availability of power for re-charge purposes, requiring the ESDs to retain their charged capacity for longer periods. These differences have implications in selecting the right technology to serve these emerging ESD usages in the datacenter.

VII. EVALUATION UNDER REALISTIC ESD TECHNOLOGIES

Next, we analyze the cost-performance trade-offs when these emerging usages are served by realistic ESD such as: Lead-Acid (LA), Lithium-Ion (LI), Fly Wheels (FW), Compressed Air (CAES) and Flow Battery (FB). Table II presents relevant ESD parameters used in our modelling framework.

A. Single scenario analysis

In this section, we evaluate the effectiveness of different ESD technologies when they are used to serve individual ESD usages. We assume that the ESDs are provisioned separately, and are not shared across different usages (including power backup).

1) ESDs for Peak shaving: We begin by comparing the cost benefits for different ESD technologies. Figure 9 (top) shows their TCO under 10% capping threshold. As can be seen, under such low capping thresholds (requiring minimal power and energy capacities), traditional electrochemical ESDs such as LI and LA incur lower cost. In addition, they also require less space due to their high energy density.

As the shaving threshold increases, energy storage requirements also increase significantly (see figure 6. TCO for shaving thresholds of 20% and 30% are shown in figures 10 and 11 (top). Under such tighter thresholds with increased area to shave, CAES offers the lowest cost. Note that, CAES deployment in datacenters are limited by their space requirements due to poor energy density and site suitability issues, as discussed before in Section III-B. Under such conditions, FBs are better alternatives incurring comparable costs ($1.25\times$-$1.8\times$) at lower volume ($25-30\%$) as CAES, and do not have any site suitability issues.

Next, we evaluate the environmental impact of ESDs based on their associated carbon emissions. We use base CO_2e to represent the emissions associated with energy consumed
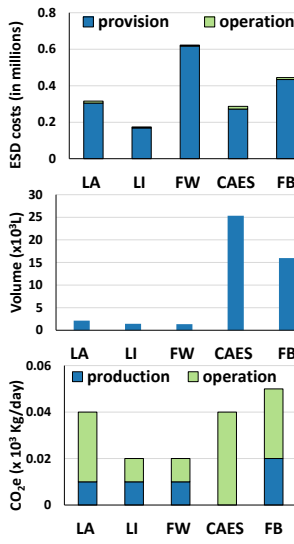
Fig. 9: PS 10%
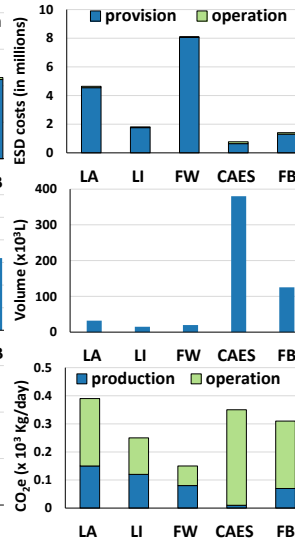Total Cost Savings: 3.5M
Base CO_2e : 77 Kg/day

Fig. 10: PS 20%
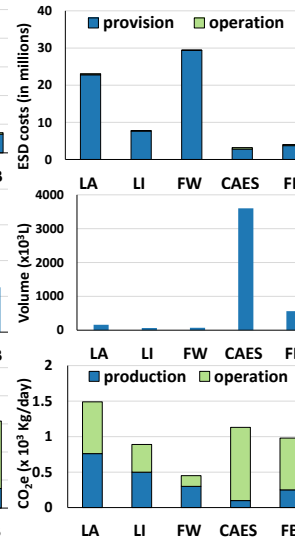Total Cost Savings: 7M
Base CO_2e : 731 Kg/day

Fig. 11: PS 30%
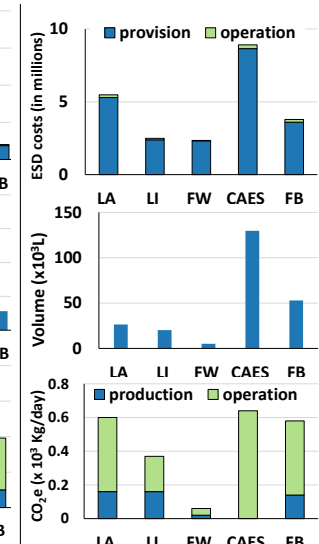Total Cost Savings: 10.5M
Base CO_2e : 2187 Kg/day

Fig. 12: PR 1MW
Market Revenue: 3.15M

under the shaved region. Moreover, use of energy storage incurs additional carbon emissions due to ESD production and operation. Figures 9, 10,and 11 (bottom) show the carbon emissions associated with ESD use, and the caption presents the base emissions rate. Lowest costing ESDs in each threshold configuration (LI for 10%, CAES for 20%, 30%), incur additional emissions in the range of $0.25\times - 0.51\times$ the base rate. If emissions during peak loads exceed $1.25\times$-$1.5\times$ than that of the base rate, using these ESDs would bring both cost as well as carbon savings. Note that, carbon emissions from operation accounts for more than 78-90% of ESD related emissions in CAES and FB, but it is only between 43-60% in other electrochemical ESDs. This indicates a potential for CAES and FB to further reduce their emissions by storing energy from low carbon sources, or by increasing their operational efficiency. Although FW offers the lowest carbon emissions, it is estimated under ideal knowledge on when to discharge and recharge. In the absence of such knowledge, continuous operation would result in high self-discharge for FWs.

Key Insights: Traditional electrochemical ESDs are cost effective under lower shaving thresholds with nominal power, energy and usage requirements. Under tighter thresholds with larger area to shave, CAES is cost effective, followed by flow batteries offering comparable cost benefits. In addition, flow batteries require less volume than CAES. Both CAES and FB have high operational losses, and correspondingly high carbon emissions. However, if the stored energy was derived from low carbon sources, CAES and FB would result in higher carbon savings in addition to cost savings.

2) ESDs for Power Regulation: In this section, we evaluate the performance of different ESDs for power regulation services. As discussed in Section II, PR requires high power capacity for charge and discharge, low energy capacity, and the ESD undergoes frequent charge-discharge cycles.

Figure 12 (top) presents the estimated ESD cost for participation in power regulation services. Among ESD technologies, only FW and LI can earn any profit ($3.5M revenue vs. $2.3M

ESD cost) under current cost levels. FW offers highest cost benefits, followed by LI (4% higher cost than FW). Power and energy needs of PR is close to that of LI technology (see figure 6), resulting in tighter provisioning, and correspondingly lower costs. In contrast to LI, Lead-Acid ESDs require high costs to accommodate their vast difference in charge/discharge rates, and they also require frequent replacements due to their poor cycle life. Note that, CAES which was attractive for tighter peak shaving, performs poorly for PR due to its high power cost and slow ramping rate. Note that, cost requirements for flow batteries is close to that of best performing ESDs such as Flywheels and LI at $1.5\times$ more cost. This is in contrast with power shaving scenario where FB's performance was close to that of the cost effective technology for PS (CAES).

Flywheel also performs well based on its volume and carbon emission metrics. LI has similar cost requirements as flywheel, but it requires $4\times$ more space and carbon emissions. FB requires $10\times$ more volume and carbon emissions than FW. However, if the stored energy is derived from a low carbon source, then emissions from FB would reduce to $7\times$ that of FW's emissions.

Key Insights: Flywheels are most suitable for regulation services on cost, space and carbon metrics, followed by LI technology. Flow batteries are comparable in cost to best performing ESDs. However, it is still not very cost effective to earn any profit under current flow battery cost and market price for PR participation.

3) ESDs for Renewable Integration: We evaluate integration of solar and wind energy under different ESD technologies. Inherent properties of RI place high power and energy capacity requirements on ESDs. For RI, figures 13 and 14 present the ESD TCO for solar and wind integration respectively. Among the ESD technologies, CAES incurs lowest cost. However, its volume requirements are very high. FB require lower cost ($1.16\times$ to $1.66\times$ compared to CAES), at considerably less space requirements (85% less space than CAES). If electrochemical ESDs are used to serve RI, it would
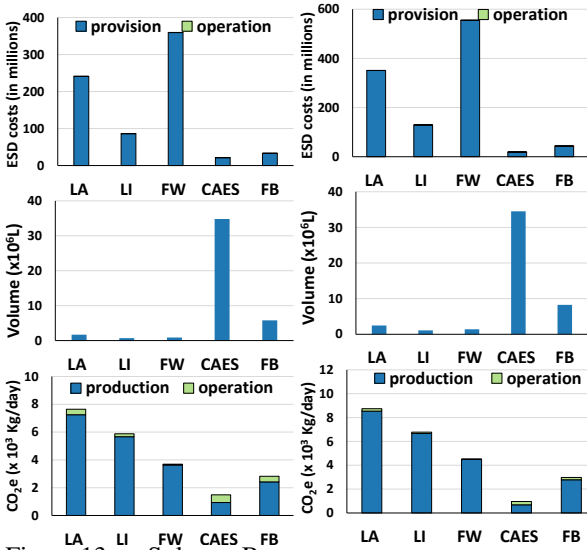
Fig. 13: Solar. Base $CO_2e : 1.19 \times 10^3$ Kg/day

Fig. 14: Wind. Base $CO_2e : 0.6 \times 10^3$ Kg/day

result in significantly high cost due to power-energy coupling. For instance, LI costs between $2.35\times$ to $4\times$ as CAES for solar and wind integration. FW also incurs significant cost due to its high energy provisioning costs.

We next evaluate the emissions associated with ESD production and operation when used for RI. We use base CO2e to represent the emissions associated with generation of the stored energy using the renewables. Figures 14 and 13 indicate that CAES incurs lowest carbon emissions (at $1.3 \times 10^3 - 1.4 \times 10^3$ Kg per day), followed by FB (at $2.82 \times 10^3 - 3.6 \times 10^3$ Kg per day). For RI, ESDs that offer lowest cost also offer lowest carbon emissions. This is in contrast with PS, where CAES and FB performed well on cost but had high emissions due to operational losses. In the absence of energy storage during periods of low renewable generation, DCs would rely on grid as the power source which emits $11 - 20\times$ more CO_2 per unit energy compared to the renewable sources (see table IV). Instead, if FB is used to store the renewable energy for use during low generation periods, our analysis indicate that it would result in only $3.23 - 6.14\times CO_2$ emissions when compared to just using the renewable sources alone.

Key Insights: For RI, CAES incurs lowest cost and carbon emissions. However, it requires very large space due to poor energy density. In contrast, FB captures a better trade-off among cost, carbon and volume metrics than other ESDs.

B. Sensitivity analysis

We next study the impact of the following characteristics on ESD performance.

1) Impact of DC characteristics: To understand the impact of temporal characteristics of datacenter power demand, we evaluate the design space using `facebook` [55] and `google` [46] power traces shown in Figures 15 and 16. Note that, in contrast to `msn`, `facebook` trace has low dynamic range (50%), whereas `google` trace has high dynamic power range (72%) and low power utilization (50%). In the interest of space, we only highlight the important observations. For peak

shaving usage, `facebook` trace results in performance similar to that of `msn`. However, the results differ for `google` power trace. For `google`, Lithium-Ion incurs lowest cost for all peak shaving thresholds (10%, 20% and 30%), as the demand profile requires smaller energy capacity. For renewable integration, ESDs performance for both these power traces are similar to that of `msn` as the supply characteristics play a significant role in determining ESD capacity.
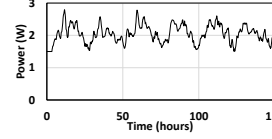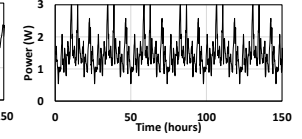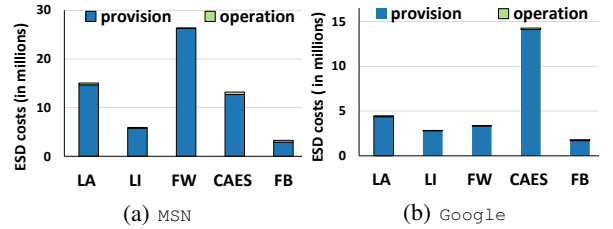

Fig. 15: Facebook trace

Fig. 16: Google trace

(a) MSN

(b) Google

Fig. 17: ESDs used to perform PS (30%) and PR (300 KW). `facebook` power trace shows similar trend as `msn`.

2) Impact of multi-purposing: Motivated by our observations that FB has performance comparable to that of the best performing ESD, we now explore the impact of employing the same ESD technology across multiple usages. We evaluate multi-purposing using the workloads of PS and PR, as it allows us to retain the datacenter configuration employing single source of power supply (i.e. grid). ESD workload consists of PS with a tighter threshold of 30% and PR with a subscription of 300 KW. Figures 17a and 17b show the ESD TCO for multi-purposing. FB incurs lowest cost (37% to 45% less cost than the next best alternative) when the ESDs are simultaneously used to perform long duration energy management for peak shaving in combination with a fast varying regulation signal. CAES, suitable for peak shaving, incurs high cost to accommodate faster discharge ramp rates of regulation. Flywheels, suitable for regulation, incurs high cost to accommodate energy needs of peak shaving. On the other hand, flow battery benefits from fast response offered by its electrochemistry as well as decoupled power-energy sizing offered by the flow system.

VIII. CONCLUDING REMARKS

Towards addressing the energy storage needs of emerging power management scenarios in datacenters, this paper explores the effectiveness of different ESD technologies based on their cost, size and environmental impact. Using realistic power traces and a modeling framework, we capture ESD technology and usage characteristics that impact its performance. Our analysis suggests that conventional electrochemical ESDs such as Lead-Acid and Lithium-Ion, used for power backup, are less suited for some of the emerging ESD usage scenarios as they are limited by their coupled power-energy properties. Our characterization effort has, for the first time, identified flow battery technology, as providing the right trade-offs across

a multitude of usages in the datacenter. Unlike Lead-Acid and Lithium-Ion, flow battery allows independent sizing of power and energy while simultaneously exploiting the benefits of electrochemical batteries for fast response and placement flexibility. In addition to cost benefits, flow batteries are promising eco-friendlier alternatives as they source their raw materials from abundant, non-toxic and greener sources.

IX. Acknowledgments

References

[1] Natural Resources Defense Council, "America's data centers consuming and wasting growing amounts of energy," https://www.nrdc.org/resources/americas-data-centers-consuming-and-wasting-growing-amounts-energy, 2015.

[2] L. A. Barroso, J. Clidaras, and U. Hölzle, *The datacenter as a computer: An Introduction to the design of warehouse-scale machines*. Morgan & Claypool Publishers, 2013.

[3] J. Hamilton, "Internet-scale service infrastructure efficiency," in *ISCA Keynote*, 2009.

[4] S. Govindan, D. Wang, A. Sivasubramaniam, and B. Urgaonkar, "Leveraging stored energy for handling power emergencies in aggressively provisioned datacenters," in *ASPLOS*, 2012.

[5] V. Kontorinis, L. E. Zhang, B. Aksanli, J. Sampson, H. Homayoun, E. Pettis, D. M. Tullsen, and T. S. Rosing, "Managing distributed UPS energy for effective power capping in data centers," in *ISCA*, 2012.

[6] S. Govindan, A. Sivasubramaniam, and B. Urgaonkar, "Benefits and limitations of tapping into stored energy for datacenters," in *ISCA*, 2011.

[7] "PJM-Market based regulation," http://www.pjm.com/markets-and-operations/ancillary-services.aspx.

[8] "Microsoft announces 175-megawatt wind farm deal, broadens renewable energy commitment," https://blogs.microsoft.com/firehose/2014/07/15/microsoft-announces-175-megawatt-wind-farm-deal-broadens-renewable-energy-commitment/, 2014.

[9] "Google datacenters - Renewable energy," https://www.google.com/about/datacenters/renewable/.

[10] "Facebook's next data center to rely only on renewable energy," http://www.computerworld.com/article/2945045/data-center/facebooks-next-data-center-to-rely-only-on-renewable-energy.html.

[11] D. Wang, C. Ren, A. Sivasubramaniam, B. Urgaonkar, and H. Fathy, "Energy storage in datacenters: what, where, and how much?" in *SIGMETRICS 2012*, 2012.

[12] H. Chen, Z. Liu, A. K. Coskun, and A. Wierman, "Optimizing energy storage participation in emerging power markets," in *IGSC*, 2015.

[13] Y. Shi, B. Xu, B. Zhang, and D. Wang, "Leveraging energy storage to optimize data center electricity cost in emerging power markets," in *E-ENERGY*, 2016.

[14] C. Li, R. Wang, T. Li, D. Qian, and J. Yuan, "Managing green datacenters powered by hybrid renewable energy systems," 2014.

[15] I. Goiri, W. Katsak, K. Le, T. D. Nguyen, and R. Bianchini, "Parasol and greenswitch: Managing datacenters powered by renewable energy," in *ASPLOS*, 2013.

[16] "Global lead acid battery market volume, by application," http://www.grandviewresearch.com/industry-analysis/lead-acid-battery-market, 2017.

[17] M. Park, J. Ryu, W. Wang, and J. Cho, "Material design and engineering of next-generation flow-battery technologies," *Nature Reviews Materials*, 2016.

[18] M. Skyllas-Kazacos, M. Chakrabarti, S. Hajimolana, F. Mjalli, and M. Saleem, "Progress in flow battery research and development," *Journal of The Electrochemical Society*, no. 8, 2011.

[19] P. Alotto, M. Guarnieri, and F. Moro, "Redox flow batteries for the storage of renewable energy: A review," *Renewable and Sustainable Energy Reviews*, 2014.

[20] M. C. McManus, "Environmental consequences of the use of batteries in low carbon systems: The impact of battery production," *Applied Energy*, vol. 93, 2012.

[21] A. C. Riekstin, S. James, A. Kansal, J. Liu, and E. Peterson, "No more electrical infrastructure: towards fuel cell powered data centers," *ACM SIGOPS Operating Systems Review*, vol. 48, no. 1, 2014.

[22] CNET, "Google uncloaks once-secret server," https://www.cnet.com/news/google-uncloaks-once-secret-server-10209580/, 2009.

[23] Microsoft Server and Cloud Platform Team , "Microsoft reinvents datacenter power backup with new Open Compute Project specification," https://blogs.technet.microsoft.com/hybridcloud/2015/03/10/microsoft-reinvents-datacenter-power-backup-with-new-open-compute-project-specification/, 2015.

[24] P. Institute, "National survey of datacenter outages," http://www.ponemon.org/local/upload/file/Data_Center_Outages.pdf, 2010.

[25] S. McCluer and J.-F. Christin, "Comparing data center batteries, flywheels, and ultracapacitors," http://www.apc.com/salestools/DBOY-77FNCT/DBOY-77FNCT_R2_EN.pdf?sdirect=true.

[26] D. Larcher and J. Tarascon, "Towards greener and more sustainable batteries for electrical energy storage," *Nature chemistry*, vol. 7, no. 1, 2015.

[27] L. Oliveira, M. Messagie, S. Rangaraju, J. Sanfelix, M. H. Rivas, and J. V. Mierlo, "Key issues of lithium-ion batteries - from resource depletion to environmental performance indicators," *Journal of Cleaner Production*, 2015.

[28] I. Hadjipaschalis, A. Poullikkas, and V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications," *Renewable and sustainable energy reviews*, vol. 13, no. 6, 2009.

[29] K. Lin, Q. Chen, M. R. Gerhardt, L. Tong, S. B. Kim, L. Eisenach, A. W. Valle, D. Hardee, R. G. Gordon, M. J. Aziz, and M. P. Marshak, "Alkaline quinone flow battery," vol. 349, no. 6255, 2015.

[30] B. Huskinson, M. P. Marshak, C. Suh, S. Er, M. R. Gerhardt, C. J. Galvin, X. Chen, A. Aspuru-Guzik, R. G. Gordon, and M. J. Aziz, "A metal-free organic-inorganic aqueous flow battery," *Nature*, vol. 505, no. 7482, 2014.

[31] T. Liu, X. Wei, Z. Nie, V. Sprenkle, and W. Wang, "A total organic aqueous redox flow battery employing a low cost and sustainable methyl viologen anolyte and 4-ho-tempo catholyte," *Advanced Energy Materials*, vol. 6, no. 3, 2016.

[32] A. Tang, J. Bao, and M. Skyllas-Kazacos, "Studies on pressure losses and flow rate optimization in vanadium redox flow battery," *Journal of power sources*, 2014.

[33] J. Sullivan and L. L. Gaines, "A review of battery life-cycle analysis: State of knowledge and critical needs," 2010.

[34] US EPA, "Application of life-cycle assessment to nanoscale technology: Lithium-ion batteries for electric vehicles," Tech. Rep. EPA 744-R-12-001, 2013.

[35] W. Torell, "Lifecycle carbon footprint analysis of batteries vs. flywheels," http://www.apc.com/salestools/VAVR-9KZQVW/VAVR-9KZQVW_R0_EN.pdf.

[36] P. Denholm and G. L. Kulcinski, "Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems," *Energy Conversion and Management*, vol. 45, no. 13, 2004.

[37] M. Arbabzadeh, J. X. Johnson, R. De Kleine, and G. A. Keoleian, "Vanadium redox flow batteries to reach greenhouse gas emissions targets in an off-grid configuration," *Applied Energy*, vol. 146, 2015.

[38] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," *Progress in Natural Science*, 2009.

[39] US Dept. of Energy, "Advanced materials and devices for stationary electrical energy storage applications," 2010.

[40] C. P. De Leon, A. Frías-Ferrer, J. González-García, D. Szánto, and F. C. Walsh, "Redox flow cells for energy conversion," *Journal of Power Sources*, 2006.

[41] L. Liu, C. Li, H. Sun, Y. Hu, J. Gu, and T. Li, "BAAT: towards dynamically managing battery aging in green datacenters," in *DSN*, 2015.

[42] R. Singh, D. Irwin, P. Shenoy, and K. K. Ramakrishnan, "Yank: Enabling green data centers to pull the plug," in *NSDI*, 2013.

[43] F. Kong and X. Liu, "Greenplanning: Optimal energy source selection and capacity planning for green datacenters," in *ICCPS*, 2016.

[44] L. Liu, C. Li, H. Sun, Y. Hu, J. Gu, T. Li, J. Xin, and N. Zheng, "HEB: deploying and managing hybrid energy buffers for improving datacenter efficiency and economy," in *ISCA*, 2015.

[45] I. Narayanan, D. Wang, A. A. Mamun, A. Sivasubramaniam, and H. K. Fathy, "Should we dual-purpose energy storage in datacenters for power backup and demand response?" in *HOTPOWER*, 2014.

[46] X. Fan, W.-D. Weber, and L. A. Barroso, "Power provisioning for a warehouse-sized computer," in *ISCA*, 2007.

[47] D. Wang, C. Ren, S. Govindan, A. Sivasubramaniam, B. Urgaonkar, A. Kansal, and K. Vaid, "ACE: Abstracting, characterizing and exploiting peaks and valleys in datacenter power consumption," in *IISWC*, 2013.

[48] Q. Wu, Q. Deng, L. Ganesh, C.-H. Hsu, Y. Jin, S. Kumar, B. Li, J. Meza, and Y. J. Song, "Dynamo: Facebook's data center-wide power management system," in *ISCA*, 2016.

[49] A. Mamun, I. Narayanan, D. Wang, A. Sivasubramaniam, and H. Fathy, "Multi-objective optimization of demand response in a datacenter with lithium-ion battery storage," *Journal of Energy Storage*, 2016.

[50] A.-A. Mamun, I. Narayanan, D. Wang, A. Sivasubramaniam, and H. K. Fathy, "Multi-objective optimization to minimize battery degradation and electricity cost for demand response in datacenters," in *ASME 2015 Dynamic Systems and Control Conference*, 2015.

[51] D. A. Notter, M. Gauch, R. Widmer, P. Wager, A. Stamp, R. Zah, and H.-J. Althaus, "Contribution of li-ion batteries to the environmental impact of electric vehicles," *Environmental science & technology*, 2010.

[52] M. Zackrisson, L. Avellán, and J. Orlenius, "Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles–critical issues," *Journal of Cleaner Production*, 2010.

[53] K. Le, R. Bianchini, T. D. Nguyen, O. Bilgir, and M. Martonosi, "Capping the brown energy consumption of internet services at low cost," in *IGCC*, 2010.

[54] G. Chen, W. He, J. Liu, S. Nath, L. Rigas, L. Xiao, and F. Zhao, "Energy-aware server provisioning and load dispatching for connection-intensive internet services," in *NSDI*, 2008.

[55] Y. Chen, A. Ganapathi, R. Griffith, and R. Katz, "The case for evaluating mapreduce performance using workload suites," in *MASCOTS*, 2011.

[56] B. Xu, Y. Dvorkin, D. S. Kirschen, C. Silva-Monroy, and J.-P. Watson, "A comparison of policies on the participation of storage in US frequency regulation markets," *arXiv preprint arXiv:1602.04420*, 2016.

[57] "National solar radiation database," http://rredc.nrel.gov/solar/old_data/nsrdb/.

[58] "Wind integration toolkit," http://www.nrel.gov/grid/wind-toolkit.html.

[59] C. Ren, D. Wang, B. Urgaonkar, and A. Sivasubramaniam, "Carbon-aware energy capacity planning for datacenters," in *MASCOTS*, 2012.

[60] US EIA, "Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook," Tech. Rep., 2016.