COPA: Highly Cost-Effective Power Back-Up for Green Datacenters

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Abstract—Traditional datacenters employ costly diesel generators (DG) and uninterrupted power supplies (UPS) to back up power. However, some or even all racks of a green datacenter can still be powered by renewable energy during grid power outages. This makes the utilization of the DGs and UPSs in green datacenters significantly lower than in traditional datacenters. In this paper, we propose a highly cost-effective power back-up (COPA) approach for green datacenters by leveraging the availability characteristics of renewable energy as well as grid power outages. COPA contributes three new techniques. The first technique, called least UPS capacity planning, determines the least rated power capability and runtime of the UPSs to guarantee the normal operations of a green datacenter during grid power outages. The second technique, named cooperative UPS/renewable power supply, employs UPS and renewable energy at the same time to supply power to each rack when grid power fails. The last one, dubbed renewable-energy-aware dynamic power management, controls the power consumption dynamically based on the available capacity of renewable energy and UPS. We build an experimental cluster consisting of 10 servers, and use four representative benchmarks as well as verified data about the availability characteristics of solar and wind energy to evaluate COPA. The results show that COPA reduces 47 percent and 70 percent of the power back-up cost for a solar energy powered datacenter and a wind energy powered datacenter, respectively. Moreover, COPA guarantees the application’s Service Level Agreement (SLA) for at least 20 minutes (over 79 percent outages) and 56 minutes on average while enabling the back-up power to last for at least 2 hours and for 3 hours on average, which cannot be achieved by other under-provisioning power back-up approaches.

Index Terms—Datacenter power backup, renewable energy, cooperative power distribution, dynamic power management

1 INTRODUCTION

The huge amount of grid energy consumed by modern datacenters is exacerbating both energy crisis and global warming because fossil fuel is currently the main source of grid power. On the one hand, a recent report shows that the energy consumption of U.S. datacenters is expected to reach approximately 73 billion kilowatt-hour (KWh) in 2020 [1]. On the other hand, as datacenter footprints continue to expand, greenhouse gas emissions would exceed 100 million tons per year if fossil fuel continues to be the main source for generating energy [2], [3].

Faced by such a burdensome case, Internet giants including Apple [4], Google [5] and Facebook [6] started to use renewable energy powered datacenters (called green datacenters) [7]. Moreover, these giants are still rapidly increasing renewable energy investments in their datacenters [8]. However, due to its instability and intermittence, renewable energy is typically used as a supplement of grid power in a green datacenter.

Power back-up is indispensable for datacenters because grid power outages are unavoidable. Most traditional datacenters employ diesel generators (DG) and uninterrupted power supplies (UPS) to sustain operations when grid power fails [10]. A charged UPS can supply power immediately but it needs to recharge after a limited time interval. A DG, on the contrary, can last for a long time but cannot supply power immediately because it needs time (e.g., 2 minutes) to boot up. Therefore, UPSs typically supply power for a datacenter before DGs boot up. Such power back-up expenditure is over 20 percent of the power infrastructure cost of a datacenter [11], [12]. Consequently, the direct cost of UPSs and DGs amounts to 2.68 millions of dollars per year for a 20 megawatt (MW) datacenter [13].

However, the utilization of such costly UPSs and DGs is extremely low because they are power back-up facilities which are naturally idle most of the time. On the one hand, U.S. datacenters experience an average of only 2.66 grid power failures per year according to a recent survey [9]. On the other hand, Fig. 1 shows that 79 and 90 percent of datacenter power outages are shorter than 20 minutes and 2 hours,
respectively. This indicates that 79 and 90 percent of datacenters only use their UPSs and DGs for at most 52 minutes and 5.2 hours on average per year, respectively.

When renewable energy is employed in a datacenter, the utilization of the UPSs and DGs becomes even significantly lower, as shown in Fig. 2. The reason is that renewable energy may supply power for some racks when the grid power fails. As such, the UPSs and DGs are not fully utilized even during a grid power outage. Moreover, both UPSs and DGs suffer from aging, which requires them to be replaced after a fixed time even though they are not used (e.g., usually 4 years for acid-lead UPSs and 12 years for DGs [14]). This results in extremely low cost-effectiveness of the power back-up facilities of a green datacenter. To improve the cost-effectiveness, there are three questions to be answered. (1) Are DGs still needed? (2) Given the existing renewable energy, what are the suitable power capacity and runtime of UPSs? (3) What is the power supply strategy (e.g., what is the power back-up share between renewable energy and UPSs)? Although prior work [13] proposed a cost-performance-availability strategy for different levels of power back-up under-provisioning, it does not consider renewable energy in green datacenters. Zhou et al. [15] propose that renewable energy can be used to under-provision the grid power infrastructure. However, they do not consider power back-up cost with renewable energy.

In this paper, we answer these three questions by proposing a highly COnsider power back-up cost (COPA) approach that leverages the availability characteristics of renewable energy as well as grid power outages of a green datacenter. COPA removes DGs and contributes three novel techniques. The first technique, called least UPS capacity planning, determines the least rated power capacity and runtime, which are the two key parameters, of a UPS that can guarantee the normal operations of a datacenter during grid power outages. The second technique, called cooperative UPS/renewable power supply, employs UPS and renewable energy at the same time to power each rack during grid power outages. The third technique, called renewable-energy-aware dynamic power management, dynamically controls the power consumption based on the available capacity of renewable energy and UPSs. It combines different technologies including power throttling [18], [19], [20] and workload migration [21], [22] for different levels of renewable energy and UPS capacity. The first technique reduces the power back-up cost directly while the second and third techniques decrease the cost indirectly by sustaining the power as long as possible during grid power outages.

In particular, we make the following contributions:

(1) We propose a technique called least UPS capacity planning to leverage the availability characteristics of renewable energy and grid power outage characteristics of datacenters to significantly improve the cost-effectiveness of power back-up facilities.

(2) Under the constraint of high cost-effectiveness, we develop two techniques: cooperative UPS/renewable power supply and renewable-energy-aware dynamic power management to supply power as long as possible during grid power outages, further improving the cost-effectiveness.

(3) We called the proposed techniques COPA, which can reduce 47 and 70 percent of power back-up costs for a solar and a wind energy powered datacenters, respectively. Furthermore, COPA lasts for at least 2 hours and on average 3 hours, which cannot be achieved by other power back-up techniques.

The rest of this paper is organized as follows: Section 2 provides background and motivation. Section 3 depicts the design of COPA. Section 4 presents the experimental setup. Section 5 provides the results and analysis. Section 6 describes related work and Section 7 concludes the paper.

2 BACKGROUND AND MOTIVATION

2.1 Power Back-Up Facilities of a Datacenter

The primary power supply of a traditional datacenter is the grid power. As shown in Fig. 3, line A from the grid connects to a number of Power Distribution Units (PDU) providing power to the racks. Datacenters are also equipped with UPSs and DGs which act as a secondary power supply during grid power outages. The distributed UPS units track the supply voltage and frequency variations of the corresponding racks. When a grid power failure occurs, UPSs can quickly turn on their internal DC-AC inverter and supply power to the servers. Meanwhile, an Automatic Transfer Switch (ATS) detects grid failures and

![Fig. 1. The frequency and average duration of grid power outages of U.S. datacenters [9].](image1)

![Fig. 2. The comparison of averaged utilizations of UPSs and DGs in datacenters with and without renewable energy (normalized to utilization of the grid power) [9], [16], [17]. Since the renewable energy can power some, or all servers when unplanned grid power fails, the UPSs and DGs utilization of green datacenters is lower.](image2)

![Fig. 3. Power backup facilities of a datacenter.](image3)
subsequently switches the power load from the grid to the DGs. It takes about 2 minutes to boot up the DGs and switch the power supply to servers from UPSs to DGs. Subsequently, the DGs power the whole datacenter independently and the UPSs are switched to standby mode by turning off the inverter because power supply voltage level has returned to normal.

When renewable energy is employed in a datacenter, its energy assumes a higher priority than grid power to be fully utilized by the racks, as shown in Fig. 3. The Central Controller (CC) can get the status of the renewable energy periodically through a sensor and determines the number of renewable-energy-powered racks by controlling the relays (S1, S2, and S3) over the Ethernet. Renewable energy supply is not influenced by grid failures because renewable power employs a different transmission line (line 2) from that (line 3) for the grid power. Therefore, during grid outages, the CC obtains the available renewable power and switches some relays such as S2 and S3 to terminal a to let renewable energy power some racks. The UPSs of these racks are still in standby mode. However, UPSs and DGs now power the other racks, previously powered by the grid, by switching S1 to terminal b. It is obvious that the utilization of DGs and UPSs becomes lower when using renewable energy.

### 2.2 High Cost of Power Back-Up Solutions

Fig. 4 shows the annual amortized cost for power back-up infrastructure for different datacenter capacities [13]. As can be seen, power back-up cost increases proportionally with the power capacity of datacenters. For instance, for a 20 MW (megawatt) datacenter, the power back-up cost amounts to 2.68 million dollars per year. Moreover, it is predicted that the power of most datacenters can reach up to 100 MW [23], [24] in the near future. This indicates that the power back-up cost of future datacenters would be extremely high. When renewable energy is employed, the back-up cost is further increased. Assuming that the power back-up cost ($C_{pb}$) can previously handle $n$ grid outages per year. With renewable energy, it only needs to handle $m$ ($m \leq n$) grid power outages per year. The cost therefore relatively increases by $C_{pb}/m - C_{pb}/n$. Therefore, reducing the power back-up cost of datacenters is urgently needed.

### 2.3 Datacenter Availability Level

Four datacenter availability levels (Tier 1 to 4) have currently been established [11]. Tier 1 is the lowest level while Tier 4 is the highest, with complete DG and UPS systems. Tier 1 specifies the annual grid outage up to 28.8 hours; Tier 2 specify 22 hours; Tier 3 specifies 1.6 hours; and Tier 4 specifies only 0.4-hour of annual grid outage, or 99.999 percent availability. The tier level drives the design specifications for new datacenters. In the financial industry, high availability and fault tolerance (that is, typically Tier 3 and Tier 4) are required to support $24 \times 7$ financial transaction activities and funds exchanges. For other organizations (such as universities), a lower fault tolerance is acceptable.

### 3 DESIGN PRINCIPLES

#### 3.1 COPA Architecture

COPA is a highly cost-effective power back-up approach for green datacenters. COPA aims at a better trade-off between power back-up cost, performance, and availability of datacenters compared to previous solutions. The COPA architecture is shown in Fig. 5. To decrease the impact of voltage transients, frequency distortions, and harmonics on the grid, we directly connect renewable power supplies to PDUs. In other words, we supply power for the racks by the two separated lines (one for grid power and one for renewable power). We adopt distributed UPS design (one UPS for each rack) which is popular in today’s datacenters [25], [26] due to its reliability and cost advantage over conventional centralized UPS placement [27].

COPA removes DGs and only employs UPSs for two reasons: (1) The cost of a DG is high and increases almost linearly with its peak power [13]. In contrast, the cost of a UPS rises very slowly with provisioned runtime. For instance, a $20 \times$ increase in UPS runtime (from 2 mins to 42 mins) leads to an overall cost increment of only 24 percent (from 1.34 to 1.66 million dollars) for a 10 MW datacenter [13]. (2) Unlike UPS that can supply power immediately, a DG needs tens of seconds to boot up. That is, removing UPSs would make datacenters unavailable during a grid power outage, but removing DGs would not. Therefore, it is feasible as well as cost-effective to remove DGs and only use larger UPSs.

COPA consists of three key techniques as shown in Fig. 5: least UPS capacity planning, cooperative UPS/renewable power supply, and renewable-energy-aware dynamic power management. Least UPS capacity planning determines the least rated power capacity and runtime, which are the two key parameters, of a UPS that can guarantee the normal operations of a datacenter during grid power outages. COPA adaptively switches the power supply between renewable energy and UPSs during a grid power outage. As such, the
cases of power supply can be: (1) renewable energy is abundant and can power the whole datacenter independently. The excess energy can charge the UPSs. (2) The renewable power is insufficient and UPSs need to supplement power. (3) UPSs power the servers independently when renewable power is unavailable. Least UPS capacity planning is designed to configure the exact UPS capacity to effectively cooperate with renewable energy and to reduce the cost of power back-up facilities.

Note that datacenters without DGs may go down due to insufficient power (e.g., the (2) and (3) cases mentioned above) during long-time grid power outages. However, it is acceptable for some datacenters with low fault tolerance (e.g., datacenters for science computation) [11]. For high-availability datacenters, we can configure large UPS capacity according to the actual situation. In this paper, we consider highly cost-effective power back-up configuration in green datacenters and we also propose two techniques to improve the availability and performance of green datacenters as much as possible.

Cooperative UPS/renewable power supply and renewable energy aware dynamic power management address the challenges caused by the time-varying and intermittent characteristics of renewable energy, as well as the limited UPS capacities. Cooperative UPS/renewable power supply employs UPS and renewable energy at the same time to power each rack when grid power fails, which leverages the battery discharge characteristics to prolong the runtime of UPSs. Renewable energy aware dynamic power management dynamically controls the power consumption based on the available capacity of renewable energy and UPSs. It combines several technologies such as changing the CPU power state and triggering workload migration by considering the applications’ characteristics to keep servers running.

In summary, least UPS capacity planning reduces the back-up cost explicitly while cooperative UPS/renewable power supply and renewable energy aware dynamic power management decrease the cost implicitly.

### 3.2 Least UPS Capacity Planning

#### 3.2.1 Overview

Planning the UPS capacity aiming for high cost-effectiveness is very challenging. First, too large UPS capacity results in low utilization and in turn low cost-effectiveness whereas too small UPS capacity reduces the performance and availability of a datacenter. Second, the grid power outage is inherently unpredictable and renewable energy is generally unstable. Least UPS capacity planning addresses these challenges by leveraging the availability features of renewable energy and grid power outage characteristics.

#### 3.2.2 Pre-Analysis for Planning UPS Capacity

Two factors generally determine the rated capacity of a UPS: power capacity ($P_{ups}$) and runtime ($RL_{ups}$). The rated $P_{ups}$ needs to satisfy the power demand for running the datacenter workloads normally. The $RL_{ups}$ refers to the longest duration when a UPS operates normally. Further, the less workload (that is, less than rated $P_{ups}$) powered by a UPS, the longer the UPS can last (details in Section 3.3). Green datacenters typically prefer to use renewable energy to power their workloads. But if it is insufficient, the UPS would supplement the difference when a grid power outage occurs. Therefore, the availability feature of renewable energy and grid power outage characteristics have a vital impact on UPS capacity.

For the $RL_{ups}$, although the actual runtime of a UPS varies with the time-varying renewable energy, we only consider the rated $RL_{ups}$. This indicates the UPS can supply power $RL_{ups}$ hours for the datacenter with normal operations, which is influenced by the outage characteristics of grid power. Grid power outages can be characterized by two factors: outage duration ($T_o$) and outage duration distribution ($D_o$). Fig. 1 shows these two factors. For example, the 1-5 min and 5-20 min outages account for 42 and 20 percent of all grid power outages, respectively.

As for the $P_{ups}$, it is mainly influenced by renewable energy because a UPS is activated to supplement insufficient renewable power. The renewable power can also be characterized by two factors: available renewable power ($P_{re}$) and power availability distribution ($D_{re}$). We leverage the verified data of the National Solar Radiation Database (NSRDB) provided by National Renewable Energy Laboratory (NREL [28]) to analyze the solar and wind power availability. Figs. 6a and 6b show the solar and wind power of a day averaged over a month for the site #726,798 (United States Air Force number) [28]. The power capacity factor is defined as the real power output divided by the rated power.

![Solar and wind power distribution on a day.](image_url)

**Fig. 6.** Solar and wind power on a single day (orange line) and on a day averaged over a month (blue line) for the site #726,798 (United States Air Force number) [28].
during a day. From these figures, we observe the intermittency and variation of solar and wind power, which makes the determination of $P_{re}$ and $D_{re}$ challenging. Moreover, Figs. 6a and 6b show that the power capacity factor of solar energy is significantly different from that of the wind energy, indicating that the UPS configurations for solar and wind energy should be different.

Fig. 6c shows the accumulated time for each power capacity factor range for solar energy in a day, which intuitively reflects $P_{re}$ and $D_{re}$. As can be seen, in 9 hours (24 × (3/8)) of a day, the solar power capacity factor is less than 0.1. This indicates the solar energy is almost unavailable for 37.5 percent of a day. We call this duration the intermittence duration ($I = I_1 + I_2$, as shown in Fig. 6a) of solar energy. On the contrary, there are only 3 hours when power capacity factor is larger than 0.9, which can support the datacenter to operate normally in practice. Fig. 6d shows that wind power is relatively stable and its power capacity factor is larger than 0.5 for most of the day, which can provide more power than the solar energy. Note that the intermittence duration of wind energy (e.g., 20 minutes) is much shorter than that of solar energy, as shown in Figs. 6a and 6b. This indicates that UPS power capacity should be smaller in case of wind energy compared to solar energy for highly cost-effective power backup facilities.

### 3.2.3 Planning UPS Capacity

We now determine the two factors of UPS capacity for a datacenter equipped with renewable energy: rated power ($P_{ups}$) and runtime ($RL_{ups}$). We use the mathematical expectation (ME) of renewable power and grid power outage durations to determine UPS capacity. In statistics, ME is theoretically approaching to the mean value of a random variable if the random experiment generating the variable’s values is repeated for unlimited times. In practice, ME represents one’s expectation for the value of a random variable to occur most frequently.

We assume that renewable power and grid power outage duration are two random variables. As a datacenter typically operates for a long time (e.g., 10—20 years) after it is constructed, the two variables will repeatedly generate a large number of values. Although this number is not unlimited large in theory, it is large enough in practice to use ME to approximately represent the values that occur the most frequently. That is, we use the ME of the renewable power and that of the grid power outage durations to represent the most frequent power that the renewable energy can provide and the most frequent grid power failure duration that may occur, respectively. Subsequently, we leverage these two MEs to determine the rated power capacity and runtime of the UPS for a datacenter.

#### Planning the Rated Runtime of a UPS

We calculate $RL_{ups}$ based on the ME of grid power outage durations ($E(T_{o})$), as shown in Formula (1):

$$\begin{align*}
RL_{ups} &= \min\{E(T_{o}), I_{re}\} \\
E(T_{o}) &= \sum T_{o} T_{o} \times D_{o}
\end{align*}$$

where $T_{o}$ is the grid power outage duration; $D_{o}$ is its distribution (in percent); and $I_{re}$ is the intermittency duration of renewable energy that can be observed from statistic power data, as shown in Figs. 6a and 6b.

For high cost-effectiveness, we set $RL_{ups}$ to the minimum value of $E(T_{o})$ and $I_{re}$. $E(T_{o})$ reflects the characteristics of grid power outages whereas $I_{re}$ reflects the intermittency duration (or availability) feature of renewable energy. When $E(T_{o})$ is smaller than $I_{re}$, it seems that taking $E(T_{o})$ as the $RL_{ups}$ would make the datacenter unavailable because the $RL_{ups}$ of the UPS is shorter than the intermittency duration of the renewable energy. This would not occur because most outage durations are much shorter than $E(T_{o})$. Moreover, some power capping techniques can prolong the UPS power supply time, guaranteeing that the datacenter does not shut down while keeping the UPS configuration highly cost-effective. This is the case when using solar energy with long intermittence intervals as the only renewable energy of a datacenter. On the other hand, when $E(T_{o})$ is longer than $I_{re}$, setting $RL_{ups}$ to $I_{re}$ also guarantees a highly cost-effective UPS configuration while keeping the possibility for shutting down a datacenter as low as possible. This is the case when using wind energy as the only renewable energy of a datacenter.

Further, we analyze how UPS cost changes with different rated runtime durations. Fig. 7 shows five cases with different rated UPS runtime durations (all cases with the same 10 MW power capacity) considering the cost and the least number of safe grid power outages that can be successfully handled. Based on Formula (1) and Fig. 1 in a solar energy powered datacenter, $E(T_{o})$ is calculated as 68 minutes. With this runtime, the UPS can safely handle at least 85 percent of the grid power outages, which costs 1.05 million dollars.

When the UPS runtime is configured to 20 minutes, it only costs 0.65 million dollars but the UPS can only handle 59 percent of the grid power outages. Compared to the UPS configured with 68 ($E(T_{o})$) minutes, its cost is reduced by a factor of 0.65× while the runtime is decreased by a factor of 2.4×. On the other hand, compared with the 120-minute or longer time grid power outages, a UPS configured with 68 minutes leads to a cost reduction of at least 2×. This indicates that a 2× higher cost only brings a 0.7× runtime improvement. Moreover, this implies that the cost of a UPS increases more sharply when its runtime is configured longer than 68 minutes, and vice versa. In addition, a UPS configured with 68 ($E(T_{o})$) minutes can supply power for at least 120 minutes (over 90 percent safe grid power outages) if we leverage dynamical power management techniques (details in Section 3.4) to tune the time and power the UPS can provide. Therefore, $E(T_{o})$ is a good trade-off for configuring UPS runtime and cost.

#### Planning the Rated Power of a UPS

We compute the rated power of a UPS $P_{ups}$ based on the difference between a datacenter’s peak power and the ME of renewable power.

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*Fig. 7. The cost variation with different rated UPS runtime lengths. Safe grid outages refers to the ones that can be safely handled.*
Since the least UPS power capacity guarantee is mainly for the case of unavailable renewable energy. We therefore evaluate the performance by employing UPS&Mig&ThrotG (detailed in Section 3.4).

\[
\begin{align*}
E(P_{re}) = & \max(P_{p} - E(P_{re}), 60\% \times P_{p}), \\
E(P_{re}) = & \sum_{k} P_{re} \times D_{re},
\end{align*}
\]

with \( P_{p} \) the peak power needed by a datacenter, \( P_{re} \) the available power of renewable energy, \( E(P_{re}) \) the ME of the available power of renewable energy, and \( D_{re} \), the distribution of renewable power. \( P_{ups} \) is set to the maximum value among the 60 percent of the peak power \( P_{p} \) of a datacenter and the difference between \( P_{p} \) and \( E(P_{re}) \). Given that a datacenter typically consumes about 60 percent of its peak power [29], the \( P_{ups} \) configured with at least 60 percent of the peak power is able to sustain normal operations in a datacenter even if renewable power is unavailable during grid power outages. We therefore select the UPS configured with 60 percent of the peak power as a candidate rated power for the UPS, as Formula (2) shows.

Further, Fig. 8 shows the performance variation of SPECjbb (an interactive application [30]) along with the UPS cost for five different UPS power provisions (all cases with the same \( E(T_{o}) \), runtime). Since the least UPS power capacity guarantee is mainly for the case of unavailable or minimal renewable energy, we adopt the UPS&Renewable Power Supply management technique to evaluate the performance (details in Section 3.4). It guarantees high performance for short outages and high availability for long outages. As can be seen, the performance of the datacenter equipped with a UPS with 50 percent of the datacenter’s peak power is obviously lower than the UPS with 60, 70, 80, and 90 percent of the peak power. We therefore should select larger power capacity. On the other hand, the performance of the datacenter with the UPS at 60, 70, 80 and 90 percent of the peak power is very close but their costs increase linearly. Therefore, the UPS with 60 percent of the peak power is a preferred performance-cost trade-off.

We present two examples here for UPS configurations in solar and wind energy powered datacenters. We compute the ME and the intermittency durations of solar energy from Fig. 6c: \( E(P_{re}) = 0.34 \), \( I_{re} = 9 \) hours, and those of the wind energy from Fig. 6d: \( E(P_{re}) = 0.66 \), \( I_{re} = 20 \) minutes. We see that the ME for solar energy is low because of the long-time zero power supply during the night and the ME of wind energy is relatively high because of its continuous power supply. Assuming that the rated renewable power is equal to \( P_{p} \), we can configure the UPS capacity with 66 percent of the peak power and 68 minutes of runtime for solar energy powered datacenters, and configure the UPS capacity with 60 percent of the peak power and 20 minutes of runtime for wind energy powered datacenters. We only determine the least UPS capacity to get a better cost-performance-availability trade-off for green datacenters. For a high-availability requirement in a specific situation, we can properly configure a larger UPS capacity.

### 3.3 Cooperative UPS/Renewable Power Supply

When a grid power failure occurs, there are three cases to supply power under the original power supply mode of a green datacenter: (1) renewable energy is sufficient; (2) renewable energy is insufficient but can power some racks and the other racks are powered by UPSs; (3) renewable energy is unavailable and all racks are powered by UPSs.

We mainly discuss case (2) which features two simultaneous power sources. In case (2), some racks that are powered by the grid are switched to UPSs to sustain power when grid power fails. The remaining racks are still powered by renewable energy and their corresponding UPSs are in standby mode, as shown in Fig. 9a. This may cause two problems. First, the UPSs are wasted for the racks powered by renewable energy. Second, when the rack-level UPSs are depleted, the corresponding racks would shut down.

We propose cooperative UPS/renewable power supply to utilize all UPSs in a balanced manner and prolong the supply time of the UPSs. During a grid power outage, we configure that each rack is simultaneously powered by both renewable energy and UPS, as shown in Fig. 9b. As such, a UPS only needs to power the remaining workload in addition to the workload powered by renewable energy in a rack, which reduces the actual power load on the UPS. According to Peukert’s law [31], the actual discharge time \( t \) of a UPS is much longer for low power draws compared to high power draws, as shown in Formula (3):

\[
t = H \times (I_{r}/I_{k})^{k} = H \times (P_{r}/P_{k})^{k},
\]

where \( H \) is the rated UPS discharge time. \( I_{r} \) and \( P_{r} \) are the rated discharge current and power, respectively. \( I_{k} \) and \( P_{k} \) are the actual discharge current and power, respectively. \( k \) is the Peukert constant and depends on the UPS type (e.g., \( k \) is between 1.1 and 1.3 for lead-acid battery). Table 1 shows...
TABLE 1

<table>
<thead>
<tr>
<th>Variant</th>
<th>OPS</th>
<th>CPS</th>
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<tbody>
<tr>
<td>All racks in datacenter</td>
<td>N</td>
<td>N</td>
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<tr>
<td>RE powered racks</td>
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<td>UPS powered racks</td>
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<td>UPS power of the datacenter</td>
<td>P_{ups}</td>
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<td>UPS rated runtime</td>
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<td>each rack demand power</td>
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N is the number of Racks of a Datacenter. n is the number of racks powered by renewable energy and m is the number of racks powered by UPS in cooperative UPS/renewable power supply mode. OPS — original Power Supply. CPS — cooperative UPS/renewable power supply.

several variables and their values for original power supply and cooperative UPS/renewable power supply. N is the number of racks of a datacenter. n is the number of racks powered by renewable energy and m is the number of racks powered by UPS in the original power supply mode. In the cooperative UPS/renewable power supply mode, since each rack is powered by renewable energy and UPS simultaneously, the number of renewable energy powered racks is N and that of UPS powered racks is also N. We compare the supply time of UPS for cooperative UPS/renewable power supply (T_{ups}) against that for the original power supply (T_{ops}), as shown in Formulas (4) and (5). As can be seen, since actual power demand for UPS has reduced (from P_{d} to P_{d} - P_{re}/N), the supply time of UPS for cooperative UPS/renewable power supply is obviously longer than that for the original power supply.

\[ T_{ups} = RL_{ups} \times \left( \frac{P_{ups}}{N} / P_{d} \right)^k \]  

\[ \Downarrow \ T_{ops} = RL_{ups} \times \left( \frac{(P_{ups}/N)/(P_{d} - P_{re}/N))}{(P_{d})} \right)^k \]  

We propose two possible implementations for cooperative UPS/renewable power supply: (1) In Fig. 9c, a server-end controller (SEC) is designed to separate the workload of a rack to different power sources. Some servers in the rack are powered by renewable energy while others are powered by UPS. For example, there are 10 servers with 2,240 W peak power in a rack; the available renewable energy is 1,344 W, which can power only 6 servers; the other 4 servers need 896 W which are powered by UPSs with rated 1,478 W (66 percent peak power for solar-powered datacenters). (2) In Fig. 9d, a power-end controller (PEC) is designed to configure a number of small-capacity UPSs. The total capacities of the small UPSs are approximately equal to the power capacity in SEC. During a grid power outage, parts of the UPSs are activated to provide the required power. For example, 5 UPSs rated 300 W power can satisfy the power demand of 1,478 W (total 1,500 ≈ 1,478 W). If there is a need for an additional 896 W of power, three more UPSs are activated. We only consider SEC in our experimental platform since it is more flexible and easier to implement compared to PEC.

Moreover, we evaluate the original power supply mode and cooperative UPS/renewable power supply mode (SEC solution) from two aspects for a 4-hour grid power outage: UPS utilization and UPS discharge time in our experiment platform. There are 10 racks, each with 10 servers. The measured peak power of a server is 224 W. We provide 22,400 W of rated power by solar energy and a rack-level UPS with 14,780 W (66 percent of demand power) and 68-minute runtime. Fig. 10a shows that UPS utilization changes with different renewable power for the original power supply mode and only reaches 50 percent on average. The less renewable power (powering fewer racks) results in higher UPS utilization for the original power supply (powering more racks). In contrast, the UPS utilization is 100 percent all the time for cooperative UPS/renewable power supply mode because renewable energy and UPS power each rack together. Note that when renewable power is sufficient to sustain the whole datacenter, the UPS is not used for both power supply modes. Fig. 10b shows the UPS discharge time for both modes. We observe that the cooperative UPS/renewable power supply mode can sustain power for 131 minutes (35 minutes in worst case and 240 minutes in the best case) on average because of the high UPS utilization and UPS discharge characteristics (Formula (3)). For the original power supply mode, the racks that were powered on by rack-level UPSs shut down after only 35 minutes.

3.4 Renewable-Energy-Aware Power Management

Given unpredictable grid power outages, time-varied renewable power, and limited UPS capacity, our renewable-energy-aware dynamic power management dynamically employs different power capping techniques based on the discrepancy between power consumption and current power source status. It guarantees the performance and availability of services as much as possible during different durations of grid power outages. We now describe a number of power-capping techniques.

**Throttling.** Throttling is very effective for exploring the trade-off between performance and power consumption. Our system kernel can be configured with the Userspace frequency scaling governor, which provides 8 – 13 CPU frequencies, and dynamically adapts to a proper CPU frequency according to the current renewable energy and UPS state during a grid power outage. We set the CPU frequency of all servers in a rack from \( f_i \) to \( f_j \). The reduced power can therefore be expressed as \( P_{th} = P_{f_j} - P_{f_i} \), and we have the updated power demand \( P'_{d} \) of the rack: \( P'_{d} = P_{d} - P_{th}(f_i, f_j) \) (\( P_{d} \) is the power demand before throttling). We calculate power reduction \( P_{th}(f_i, f_j) \) for different CPU frequencies for each application.

**Migration.** Given insufficient renewable power and UPS power, an alternative is to migrate workloads to racks where the power supply is sufficient. After migration, some servers are shut down to reduce power consumption. We use virtual machine (VM) migration to achieve the best
workload survival, which has become the handiest approach to move the workload to other servers and to guarantee the Service-Level Agreement (SLA). We use \( n \) to denote the number of servers of a rack and \( m \) is the number of active servers after migration. That is, \( n - m \) servers \((S_0, S_1, \ldots, S_{n-m-1})\) can be shut down and the reduced power can be expressed as \( P_{\text{mig}}(S_0, S_1, \ldots, S_{n-m-1}) \). We obtain the updated power demand of the rack as follows: \( P_D' = P_D - P_{\text{mig}}(S_0, S_1, \ldots, S_{n-m-1}) \).

**Sleep and Hibernation.** Sleep mode is a power saving state as everything in the system is put into a low-power state except memory [32]. Hibernation mode offers the greatest energy savings by pushing the application state to local persistent storage and shutting down the server. Many workloads which are not real-time and run for a long time, such as scientific computation, can tolerate some delays. Such loose time demands provide the flexibility that allows the computation workloads to be unavailable during a rare and short outage. When all power sources are insufficient or unavailable, servers can be set to sleep or hibernation to reduce power consumption.

Although migration can greatly reduce power consumption, there are three situations where migration may not be considered as the first choice: (1) there must be headroom elsewhere in the rack to accommodate the migrated load and meet the application’s SLA, which may not happen if the rack is highly utilized; (2) large application state and frequent memory writing can result in long migration times; (3) when grid power is active again, we need to migrate the workload back. If UPS and throttling can handle the grid power outages while meeting the application’s SLA, the additional migration cost can be avoided. The agility of throttling makes it more attractive than migration.

We present rack-level renewable-energy-aware dynamic power management to dynamically control power consumption of a datacenter by adopting different power capping techniques. It monitors the renewable power, the status of the UPSs, and the resource usage at a coarse-grained time interval (e.g., 1 minute). According to the state, it selects proper operations to handle grid power outages. The goal is to guarantee the availability and normal performance of applications as much as possible during different durations of grid power outages.

Renewable-energy-aware dynamic power management divides the time-varying renewable energy into five levels: max, large, medium, low and min (which includes unavailable). We propose five corresponding heuristic techniques, as shown in Table 2. The max level of renewable energy can meet power demands of all servers in the rack and the excess energy can charge the UPS. In this case, our power management can guarantee the maximum performance of an application, corresponding to the Normal state. The large level of renewable energy is insufficient, but can still meet the power demand of applications with SLA in a proper throttling power state (Throt). In order to slow down the power consumption from UPSs for unknown-duration grid power outages, our power management selects a set of servers and sets proper CPU frequency for them to control their power consumption from the large level of renewable energy rather than from UPSs.

**TABLE 2**

<table>
<thead>
<tr>
<th>RE Level</th>
<th>Heuristic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>Normal</td>
<td>only use renewable energy to supply power.</td>
</tr>
<tr>
<td>large</td>
<td>Throt</td>
<td>throttling.</td>
</tr>
<tr>
<td>medium</td>
<td>UPS+Mig</td>
<td>drain UPS first before migration</td>
</tr>
<tr>
<td>low</td>
<td>UPS&amp;Mig+Throt</td>
<td>drain UPS while migration; after UPS is depleted, then throttling.</td>
</tr>
<tr>
<td>min</td>
<td>UPS&amp;Mig&amp;ThrotG</td>
<td>UPS discharge while migration, while gradually throttling.</td>
</tr>
</tbody>
</table>

Assuming that there is a headroom in a rack that allows to migrate workloads to fewer servers with little performance impact, the medium level of renewable energy can meet the power demand after migration. For example, there are 10 servers and 30 percent of headroom in the rack. We can seamlessly migrate the workloads of 3 servers to the other 7 servers. Renewable-energy-aware dynamic power management selects the UPS+Mig technique to handle the grid power outages for the medium level. In this case, UPSs are first activated and cooperate with renewable energy to supply power. The power management defers the migration operation until the UPS capacity reaches the residual capacity needed for migration (~4 minutes for migrating 10 GB application state). The number of servers from which the workload is to be migrated depends on how many servers need to be shut down within a limited power budget.

Renewable-energy-aware dynamic power management employs the UPS&Mig+Throt technique for the low renewable energy level which even cannot meet the power demand after migration. It first activates UPSs to supplement renewable energy and migration is performed at the same time to reduce overall power consumption. When UPSs are depleted, throttling is employed to control the power demand within the current power budget. The power management delays the throttling to minimize the performance degradation during grid power outages.

When renewable energy is in the min level (including unavailable) which cannot meet the power demand after migration and the lowest throttling state, the UPS is the main power source. We need not to only consider the performance of applications but also prolong the UPS’s runtime as much as possible because of the unknown grid power outage duration. Our power management therefore employs the UPS&Mig&ThrotG technique to sustain power. First, UPSs are activated and workloads are migrated to fewer servers to reduce power requirement. Meanwhile, it starts by throttling at full performance mode (assuming grid outage will be short), then gradually transitions to lower power modes which can slow down the discharging of the UPS, and finally (when UPS batteries are depleted) uses the sleep or hibernate techniques. UPS&Mig&ThrotG guarantees high performance for short outages and high availability for long outages as much as possible.

It is worth noting that, if renewable energy is in the medium, low or min level during a power outage, some
virtual machines should be migrated. The job scheduler is aware of this situation and distributes new jobs in the job queue to the machines that do not need to migrate jobs.

4 Experimental Setup

We use 10 identical servers with 32-core 3.2 GHz Intel(R) Xeon(R) E5-2630 v3 processors, 64 GB DRAM, and 1 Gbps Ethernet interface in a rack and run our applications hosted on the Linux OS. The power consumption of each server is measured by a power meter. The server idle power is around 100 W and the peak power that we have measured is 224 W. The dynamic power consumption can be modulated with 13 CPU frequencies (from 1.2 to 2.4 GHz).

We randomly choose one of the solar and wind power production traces of one-day from NREL [28] in our experimental platform. In our setup, we provision 2,240 W of rated solar energy power and 1,478 W (2240 × 0.66) of UPS with 68-minute runtime (obtained by the Least UPS Capacity Determining technique for grid power outages). We use cpufreq (the Linux interface) [33] to implement throttling, which allows the system to set to a given CPU frequency, and leverage the KVM live migration technique [34] for migration. Moreover, we use the OS commands in Linux to implement the sleep and hibernation power saving modes.

To evaluate the efficacy of our COPA approach, we experiment with three relevant scenarios during grid power outages: (1) different availability levels of renewable energy: max, large, medium, low, and min; (2) different durations of grid power outages: 5 minutes, 20 minutes, 60 minutes, 120 minutes, and 180 minutes; (3) four representative workloads that have different characteristics and different SLA demands, as shown in Table 3. Interactive applications include SpecJbb [30], an in-memory key-value store Memcached benchmark [35], and Web-Search from CloudSuite [36]. We use mcf from SPEC CPU2017 in our experiments as a representative for a computation-intensive workload.

Because COPA power management (e.g., throttling) operates on individual servers and does not consider all servers as a whole for scheduling, the COPA approach can easily scale out to thousands of servers.

5 Results and Analysis

5.1 Cost Analysis

UPS Cost. Since the power backup infrastructure is rarely used, we ignore the operational expenditure such as the cost for management and energy loss, and only focus on the up-front procurement cost and the amortized future replacement cost, called capital expenditure (cap-ex). UPS units come with rated runtime and power capacity. We express cap-ex as amortized $/year, using a linear depreciation model. The cost values of backup infrastructure are depreciated based on their lifetime, i.e., 4 years for UPS lifetime. According to [13], the UPS cap-ex, \( C_{ups} \) ($/year) depends on the rated power capacity (\( P_{ups} \) in KW) and runtime (\( RL_{ups} \) in h), and can be expressed as:

\[
C_{ups} = P_{ups} \times RL_{ups} \times \frac{EC_{ups}}{12},
\]

where \( P_{ups} \) ($/KW/year) and \( EC_{ups} \) ($/KWh/year) represent power cost per year and energy cost per year, respectively. \( RL_{ups} \) and \( EC_{ups} \) reach 50$/KW/year and 50 $/KWh/year, respectively [37]. \( RL_{free} \) refers to the free runtime expected with rated power, and its value is 2-minute [13]. In our experiments, the UPS with 0.66 of the peak power and 68-minute runtime costs 1.39 M$/year in a solar-powered 20 MW datacenter. The UPS with 0.6 of the peak power and 20-minute runtime costs 0.78 M$/year in a wind-powered 20 MW datacenter.

Cost for Cooperative UPS/Renewable Power Supply. Cooperative UPS/renewable power supply needs additional control switches to make renewable energy collaborate with UPS in a rack (details in Section 3.3). Assuming that the number of servers in a datacenter is \( S \), we need \( S \) switches. The per switch cost is \( C_s \), and lifetime is \( T_{life} \) years. The cost for cooperative UPS/renewable power supply, \( C_{cps} \) ($/year) can therefore be expressed as:

\[
C_{cps} = \frac{S \times C_s}{T_{life}},
\]

A control switch can be implemented by a programmable chip, which costs as low as 0.14$ [38] and have 10 years of lifetime [39]. Assuming that there are 90,000 servers with 20 MW power demand of a datacenter (the peak power of each server is 224 W in our experimental platform), the cost of Cooperative UPS/renewable Power Supply for the SEC implementation equals 1.260$/year. The PEC also needs control switches to select multiple batteries, for which the cost is similar as for SEC.

Renewable Energy Cost. In green datacenters, renewable energy is used all the time but we only consider the amortized cost during the grid power outages rather than the direct construction cost because we focus on power back-up solutions. The renewable energy cost for COPA \( C_{re} \) ($/year) can be expressed as:

\[
C_{re} = C_{perKWh} \times P_{re} \times duration,
\]

where \( C_{perKWh} \) ($/KWh) represents the cost per KWh of renewable energy, \( P_{re} \) (KW) is the rated renewable power, and the \( duration \) is the total length of all grid power outages per year. Taking solar and wind energy as examples, the solar and wind energy cost \( C_{perKWh} \) is as low as 0.12$/KWh [40] and 0.1$/KWh[41, 42], respectively. The \( duration \) has 638 minutes/year in the worst case (240 minutes × 2.66/ year) for datacenters [9]. For a 20 MW datacenter, the solar energy cost and wind energy cost for COPA are only 24,000 $/year and 20,000$/year, respectively.

Now we investigate the total cost of COPA, and compare it with that of the traditional power backup infrastructure, as shown in Table 4. We see that COPA reduces 47 percent
of power backup cost for a solar-powered datacenter and 70 percent for a wind powered datacenter. In detail, COPA can save 1.26 M$ (million dollars) and 1.89 M$ per year for 20 MW solar and wind-powered datacenter, respectively.

5.2 Effectiveness of COPA
We first evaluate the performance of SPECjbb by using COPA during different durations of grid power outages and compare with the traditional power backup approach. We use the average operation/second (ops) of servers in the rack as our performance metric for SPECjbb. Fig. 11 shows the aggregated power of the 10 green-provisioned servers running SPECjbb under different levels of renewable energy. We see high variation of solar energy production over time. In this paper, we assume that the performance loss within 10 percent compared to normal performance can still meet the SLA of SPECjbb, corresponding to ≥2 GHz CPU frequency and 2,040 W power. Meanwhile, there is 30 percent headroom in the rack. In other words, the workloads of 3 servers can be migrated to the other 7 servers without performance degradation. On the other hand, more workload migration will cause larger performance loss. After migration, the 3 servers can be powered down to reduce power consumption. Subsequently, we compute the values of $P_{\text{Mig}}$ and $P_{\text{low,Throt}}$, a priori.

We compute the thresholds of the five levels of renewable energy for SPECjbb: 2,240 W (max), 2,240 W - 2,040 W (large), 2,040 W - 1,568 W (medium), 1,568 W - 840 W (low), and 840 W - 0 W (min), as shown in Fig. 11. We have evaluated the performance for all the cases of time-varying renewable energy over different grid power outage durations. We only present the performance and availability impact on applications for five representative levels of renewable power: 2240 W, 2150 W, 1800 W, 1250 W, 450 W and we assume at this moment a grid power failure occurs.

![Fig. 11. The five levels of availability of renewable energy for SPECjbb over time. The five points in different solar power levels indicate the moment when an unpredicted grid power outage occurs (e.g., an outage may be occurs in the max level or large level).](image)

The renewable-energy-aware dynamic power management of COPA employs different techniques for different levels.

**Impact of Renewable Energy Levels on Performance.** We observe the performance of a program from the moment when the solar energy is in a certain level and a grid power outage occurs at the same time to the end of the outage. Fig. 12 shows how the solar energy levels affect the performance (operations per second) of SPECjbb when using COPA. The X axis represents the five levels of the solar energy. The performance corresponding to the max level represents the one observed from the moment when the solar energy is in the max level and at this time a grid power outage occurs to the end of the outage. The same applies to other levels of renewable energy. We analyze the performance impacts for five levels of the solar energy next.

**Max Level.** From Fig. 11, we see that the solar energy can be in the max level for about 40 minutes after a grid power outage occurs. For the 5-minute and 20-minute power outages, SPECjbb can run with the maximum (full) performance, as shown in Fig. 12. However, Fig. 12 shows that SPECjbb experiences a little bit performance degradation for the 60-minute grid power outage. The reason is that the solar energy enters its large level and it can not support SPECjbb to run with the full performance after 40 minutes. In this level, the renewable-energy-aware dynamic power management in COPA employs the corresponding tuning technique to control the power consumption by Throt without using UPS, which reduces performance by 4 percent. The large level of solar energy lasts for about 50 minutes (from 40 to 90 minutes after the grid power fails). Then the solar energy enters the medium level and the power management technique employs the UPS+Mig to sustain operation which makes SPECjbb run at full performance. In summary, COPA makes a datacenter meet the SLA of applications for at least 3 hours if the grid power outage occurs at the moment when the solar energy is in its max level, as shown in Fig. 12.

**Large Level.** If the solar energy enters its large level at the moment when a grid power outage occurs, the performance is still able to meet the SLA of SPECjbb for 3 hours. The Throt is first used for 50 minutes with 96 percent of the full performance of SPECjbb. Then renewable-energy-aware dynamic power management employs UPS+Mig to sustain power with the full performance for 100 minutes, which the solar energy already enters its medium level.

**Medium Level.** If the solar energy is in its medium level and at a certain moment the grid power fails, COPA can meet the SLA of SPECjbb for 160 minutes by using UPS+Mig and UPS&$S_{\text{Mig}}$+$\text{Throt}$. Since the UPS power is enough for the medium level, migration is executed at the beginning of the $S$ level for UPS&$S_{\text{Mig}}$+$\text{Throt}$. Due to the 30 percent of headroom in the rack, we can only migrate the workloads of up...
to 3 servers to the other 7 servers, which causes little performance impact and it takes about 4 minutes for SPECjbb. When the UPSs are depleted, COPA reduces the performance by 41 percent with the lowest throttling state. We can see that COPA prolongs the supply time of UPS by 2.35× (from 68 to 160 minutes).

**Low Level.** The low level of solar energy does not meet the power demand after migration. In this case, COPA achieves full performance by using UPS&Mig+Throt for 60 minutes. Subsequently, throttling is used to reduce power consumption with a 59 percent performance degradation.

**Min Level.** If the solar energy is at its min (minimal or unavailable) level and a grid power outage occurs, renewable-energy-aware dynamic power management uses Mig&UPSS&ThrotG with gradually lower CPU frequency to provide high performance for short grid outages and high availability for long outages but with lower performance. As such, our power management can achieve the trade-off of performance and availability by using throttling.

### 5.3 Impact of Application Characteristics

For the rest of the evaluation, we consider the COPA in the solar powered datacenter (configuring UPS with 66 percent demand power and 68 minute runtime) and compare the performance and availability impact for applications with diverse characteristics.

**Memcached.** Due to high memory-related CPU stalls which are better for throttling-based techniques [44], we find that Memcached achieves better performance through throttling than SPECjbb for the low and min levels of renewable energy. For the low level of the renewable energy, the performance achieves the full performance for 60 minutes after a grid power outage occurs, then degrades to 70 percent for lowest throttling state, which is 11 percent higher than SPECjbb, as shown in Fig. 13. As for the min level, our renewable-energy-aware dynamic power management employs gradual throttling to achieve different performance levels (from high to low). The performance of Memcached is 10 percent higher than for SPECjbb for the same level on average.

**Web-Search.** The performance of Web-search is insensitive to CPU frequency. For example, the performance of Web-search can still achieve 93 percent of the full performance and meets the SLA at the lowest CPU frequency. This is beneficial to control power while achieving high performance through throttling. Web-search shows better performance than Memcached during grid power outages, as shown in Fig. 14. For the low level of the renewable energy, the performance only degrades to 93 percent of the full performance after 180 minutes, 23 percent higher than Memcached. As for the min level, the performance of different throttling state for Web-search can achieve at least 93 percent of the full performance until the UPSs are depleted.

We take mcf from SPEC CPU2017 as a representative of scientific applications. In Fig. 15, the renewable energy enters the max level at the moment when a grid power outage occurs, it can achieve full performance for 30 minutes and degrades to 94 percent, further 84, 77 percent as the renewable energy gradually falls. For the large and low renewable energy levels, proper throttling state is set based on the renewable power state without using UPSs. When renewable energy enters its min level, UPSs are activated and the lowest CPU frequency is set to prolong the UPS’s runtime with a 23 percent performance degradation. The availability of mcf is still at least 3 hours for a grid power outage.

**Key Insights.** (1) For applications with low sensitivity of CPU frequency, throttling is a good choice to control power while meeting the application’s SLA. (2) For scientific applications that can tolerate delays, we can only use throttling to the lowest CPU frequency to prolong the UPS supply time without migration.

### 5.4 Availability Analysis of Datacenters

High availability of datacenters is the guarantee of high service quality. The availability of a datacenter per year (A_{dc}) can be expressed as: \( A_{dc} = (1 - T_{dt}/T_{year}) \times 100\% \), where the \( T_{dt} \) represents the actual power-down time of a datacenter per year and \( T_{year} \) is the time of one year (24 × 365 = 8760 hours). We can see that COPA can sustain power for at least 3 hours. In most (over 90 percent) cases, \( A_{dc} \) can achieve 100 percent. In the worst case (i.e., 240 minutes for each grid power outage), \( A_{dc} \) can also achieve at least 99.97 percent.

### 6 Related Work

**Datacenter Power Backup.** Due to the high cost of power infrastructure in datacenters, several efforts on under-provisioning power infrastructures have been proposed. With power under-provisioning, backup power works not only during grid power outages, but also during the procedure for shavings the peak power and demand response [45], [46]. Wang et al. [10] explore the pros and cons of placing different energy storage devices in different layers of the power hierarchy. Narayanan et al. [47] perform a detailed study of the pros and cons when dual-purposing (outages and demand...
response) UPSs are warranted. These works do not focus on the configuration exploration of power backup for grid power outages in green datacenters.

Wang et al. [13] present cost-performance-availability trade-offs for different levels of backup under-provisioning for applications with diverse reliance on the backup infrastructure. However, this work only gives different rough power backup configurations without considering renewable energy for green datacenters. In contrast, COPA proposes a careful power backup configuration exploration by leveraging the availability characteristics of renewable energy as well as the grid power outage characteristics to significantly reduce the power backup cost, while minimizing the performance and availability impacts.

**Using Renewable Energy in Datacenters.** With the wide use of renewable energy in datacenters, many approaches have been proposed to under-provision the grid power infrastructure to save grid power investments [15], [48], [49], [50] and optimize renewable resource utilization to improve performance per Watt [51], [52], [53], [54], [55], [56]. To our best knowledge, while much prior work has focused on renewable energy, the cost-benefit power backup approaches by using renewable energy have not yet been explored so far. COPA under-provisions the power backup infrastructure reasonably.

**Power Management.** Throttling such as dynamic voltage/frequency scaling (DVFS) and migration are effective power management techniques to reduce power consumption [13], [15], [57]. However, a single power capping technique or a fixed technique combination is not enough for handling the time-varying renewable energy and unplanned (unknown-length) grid power outages. Raghavendra et al. [58] propose a hierarchy of coordinated controllers for peak and average power management across hardware and software for complex enterprise environments to minimize the performance impact. This work however does not consider power backup for grid power outages. Given the time-varying renewable energy and limited power backup capacity during unpredicted outages, COPA employs different power capping techniques for different renewable power levels in green datacenters, achieving high performance for short outages and high availability for long outages. Liu et al. [59] studied how to select a power source for normal operation rather than for backing up power in a datacenter. Recently, security has become an important concern in datacenter power management. Hou et al. [60], [61] investigate datacenter power management in the context of denial-of-service (DoS) attacks.

7 Conclusion

This paper proposes COPA, a highly cost-effective power back-up approach by leveraging the availability characteristics of renewable energy as well as the grid power outage characteristics. COPA consists of three techniques: least UPS capacity planning, cooperative UPS/renewable power supply, and renewable-energy-aware dynamic power management. Least UPS capacity planning explicitly reduces the power backup cost by reconfiguring the UPSs while cooperative UPS/renewable power supply and renewable-energy-aware dynamic power management implicitly decrease the cost by prolonging the supply time of UPS batteries as long as possible during grid power outages. As a result, COPA significantly reduces the power backup cost and substantially improves performance and availability, yielding a much improved trade-off between cost, performance, and availability for green datacenters compared to traditional power backup solutions.

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