REDUX: Managing Renewable Energy in Data Centers using Distributed UPS Systems

Xiaopu Peng, Chaowei Zhang, Christian Kauten, Jianzhou Mao, Thomas Heckwolf, and Xiao Qin
Department of Computer Science and Software Engineering
Auburn University, Auburn, AL.

***Abstract*—To environmental friendly and energy-efficient data centers, it is prudent to leverage on-site renewable sources like solar and wind. Data centers deploy distributed UPS systems to handle the intermittent nature of renewable energy. We propose a renewable-energy manager called *REDUX*, which offers a smart way of managing server energy consumption powered by a distributed UPS system and renewable energy. REDUX maintains a desirable balance between renewable-energy utilization and data center performance. REDUX makes judicious use of UPS devices to allocate energy resources when renewable energy generation is low or fluctuate condition. REDUX not only guarantees the stable operation of daily workload, but also reduces the energy cost of data centers by improving power resource utilization. Compared with existing strategies, REDUX demonstrates a prominent capability of mitigating average peak workload and boosting renewable-energy utilization.**

***Index Terms*—Renewable energy, uninterruptible power supply (UPS), distributed UPS systems, resource management, energy cost, data centers.**

I. Introduction

Existing power management techniques for data centers either overlook the usage of uninterruptible power supplies (i.e., UPS devices) or pay no attention to power-grid price fluctuation. In this study, we develop a resource manager called *REDUX* to cost-effectively allocate energy resources by incorporating a distributed UPS system tailored for renewable energy like solar.

REDUX aims to minimize energy cost by deploying UPS devices in data centers to address two challenging issues, namely, the intermittency feature of renewable energy and dynamically changing electricity price. REDUX is responsible for maintaining stable operation of daily computing workload in data centers while cutting back energy costs by improving overall energy resource utilization. Four emerging trends below strongly motivate us to contrive the REDUX system.

- Energy cost of large-scale data centers is skyrocketing.
- Consuming renewable energy in data centers brings economical and environmental benefits.
- There are pressing demands for data centers powered by cost-effective renewable energy.
- Distributed uninterruptible power supplies are increasingly popular in data centers.

In the past decades, there has been a rapid growth of data centers built for a wide range of cloud-based computing services [1]. Because cloud computing platforms are reliable, elastic, and cost effective, cloud computing housed in data centers becomes essential data processing infrastructures for the operation of businesses, academic, and governmental institutions. Massive amounts of power consumption of large-scale data centers has become a serious challenge to data center designers and operators worldwide [2]. It is evident that data centers running around the world are at a risk of doubling their energy consumption every five years [3]. To make it worse, a significant portion of electricity is generated through carbon-intensive approaches (a.k.a., brown energy), and the environmental impacts caused by these data centers are under a continuous pressure from the media and society.

In contrast to brown energy, renewable energy harvested from sources such as wind turbines and solar panels exhibits an assortment of benefits [4]. For example, most renewable energy sources are clean and produce few global warming emissions. Renewable energy offers affordable electricity that reduces energy costs. As such, a growing number of data centers have kicked off various initiatives to integrate renewable sources into power supplies. For instance, *Apple* has recently constructed a massive 100-acre solar farm adjacent to the *iCloud* data center in North Carolina. This solar farm yields 84 million kWh of clean renewable energy annually.

The integration of on-site renewable sources poses a grand challenge due to the intermittent nature of renewable energy to data-center operators [5]. In spite of this challenge, designing renewable-energy powered data centers has promising benefits beyond low carbon footprint. In particular, renewable energy supplies, being highly modular, can incrementally increase power capacity to match load growth. Such a benefit greatly reduces the over-provisioning loss of a data center, because it takes a long time period for a server load to catch up with upgraded provisioning capacity. From the perspective of construction lead-time, on-site renewable energy facilities can be constructed in a shorter time interval compared with conventional power plants [6]. Unlike traditional energy, renewable-energy price tends to remain reasonably stable after on-site installations are completed [7].

There are two widely adopted techniques to prevent costly down time incurred by power budget violations. The first approach is to intentionally over subscribe power infrastructures; the second one is called power capping (e.g., dynamic voltage and frequency scaling) [13]. More often than not, data centers powered by over-subscribed resources inevitably encounter a problem of power premium charge ascribed to the peak power. Such premium cost is a significant portion of

Table I. **Comparisons between REDUX and the existing power management techniques for data centers.**

Power Management	UPS Enabled	Renewable Energy	Management Regions	Grid Price Fluctuations	Dynamic Management	Hierarchical Design
ReUPS [8]	√	√	√	×	√	×
Greenworks [9]	√	√	×	×	×	√
iSwitch [6]	×	√	√	×	×	√
EcoPower [10]	×	√	×	√	√	×
GreenSlot [11]	×	√	×	√	√	×
GreenSwitch [12]	×	√	×	√	√	×
REDUX (This Study)	√	√	√	√	√	√

electricity bills (e.g., up to 40%). It is common that the power capping approaches result in performance degradation. To solve the aforementioned problems, Govindan *et al.* employed a centralized UPS in data centers to furnish energy during a peak demand period [14]. The UPS-based scheme effectively hides the extra power from power grids by completely shaving high-magnitude power spikes in a short time window (e.g., 1-2 hours) using UPS devices.

When it comes to long spike intervals (e.g., 8-10 hour), distributed and per-server UPS devices represent an economical solution by the virtue of battery backup. In contrast to the conventional UPS design, distributed UPS batteries allow data-center operators to readily shave peak power with stored energy [13]. The advantages of distributed UPS systems include good efficiency, high scalability, and adequate reliability. Distributed UPS systems, where a potential single point of failure is eliminated, naturally scale up with the corresponding data-center sizes. A recent study showed that a hybrid distributed UPS architecture at the power distribution unit (PDU) and server levels is a promising topology. As an example, a novel distributed battery control system was deployed in a Google state-of-the-art data center [15].

In this study, we advocate managing energy resources by leveraging a distributed UPS system to make data centers economically and environmentally friendly. We develop the *REDUX* manager to allocate renewable energy integrated with a power grid. REDUX deals with the three supply levels of renewable energy resources, namely, high, fluctuate, and low. REDUX makes judicious decisions on UPS charging and discharging with sufficient information on renewable-energy supply levels and time-dependent grid power price. For instance, REDUX makes full use of UPS devices to furnish energy resources when renewable energy generation is low or under a fluctuate condition.

One prominent feature of REDUX is that it orchestrates a desirable balance between renewable-energy utilization and data center performance. Importantly, REDUX conserves the energy cost of data centers through power resource management while offering reliable computing operations. Compared with existing strategies, REDUX demonstrates a prominent capability of mitigating average peak workload and boosting renewable-energy utilization.

The rest of the paper is organized as follows. Section II surveys the related work of energy-efficient computing, renewable energy in data centers, and distributed UPS systems. The framework and models of REDUX are detailed in Section III. Section IV articulates an array of heuristic algorithms at the heart of REDUX. Section V describes the experimental settings and results. Finally, Section VI concludes this paper.

II. Background and Related Work

Let us classify the related studies into four core areas, namely, energy-efficient computing, conserving energy in data centers, renewable energy in data centers, and distributed UPS systems. Table I summarizes the major differences between our proposed REDUX and the existing power management techniques for data centers. The overview of the compared solutions listed in Table I can be found in the rest of this section.

Energy-Efficient Computing. A large body of early studies focused on reducing power consumption of a single server by applying the dynamic voltage and frequency scaling technique (i.e., DVFS) [16], low-power chipsets [17], and advanced cooling techniques [18]. Emerging energy-management schemes aim to optimize energy efficiency of servers equipped with multi-core processors [19], GPUs [20], and smart memory cubes [21]. In contrast to the above energy-efficient computing strategies, our REDUX pays attention to reducing energy cost of large-scale data centers.

Conserving Energy in Data Centers. In recent years, there has been a pressing need to minimize the total power consumption of data centers [22] [10]. Chun *et al.* investigated a hybrid datacenter architecture mixing low power systems and high performance ones [23]. Dabbagh *et al.* developed an integrated energy-aware resource provisioning framework to optimize energy efficiency of data centers [24]. Shuja *et al.* investigated practical approaches to maximizing quality of services while minimizing energy consumption of data center resources.

Virtualization techniques have been applied to reduce the power consumption by consolidating multiple virtual machines into one physical server [25]. For example, Tseng *et al.* designed a virtual machine management strategy to predict resource utilization for upcoming videos, thereby turning off idle servers to conseve energy [26]. Another thread of techniques that minimize the electricity cost of data centers is exploiting the temporal and regional diversity of electricity prices (see, for example, [27]). The pragmatic idea of these schemes is to dynamically allocate resources to service workload in data centers with a cheap electricity price. Unlike the existing energy-saving techniques, our proposed REDUX conserves

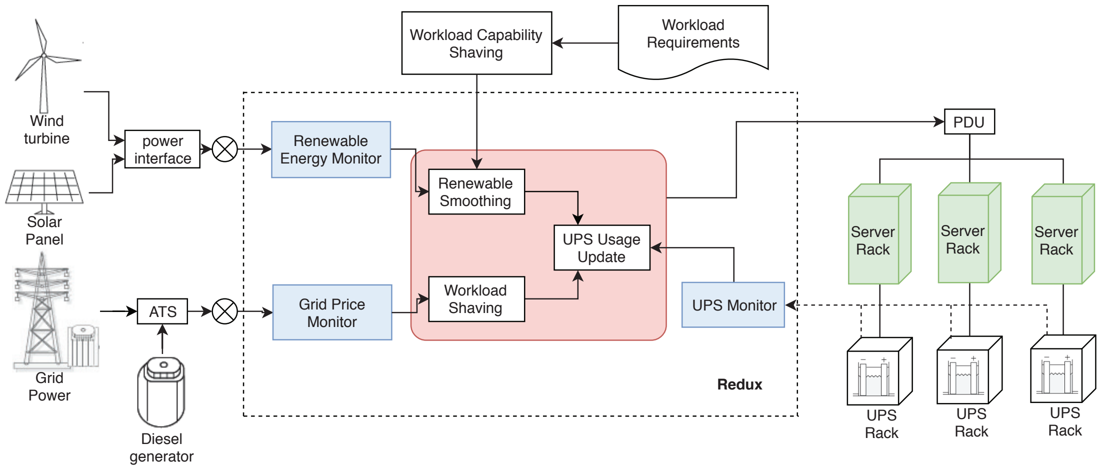

Figure 1. The framework of the *REDUX* system. REDUX orchestrates renewable energy, UPS units, and server racks according to workload requirements.

energy by taking a full advantage of renewable energy and UPS devices.

Renewable Energy in Data Centers. There are pressing demands from cloud service providers for cost-effective renewable energy to power data centers [9]. An increasing number of prior studies focused on making green data centers through the integration of renewable power sources [28] [12]. A handful of resource management techniques were developed to address the shortfall intermittency of renewable power. For example, Goiri *et al.* designed a parallel batch job scheduler to match the computational workload with solar energy supplies in a datacenter [11]. To integrate renewable energy, Guo *et al.* incorporated geographical load balancing, opportunistic workload scheduling, and thermal storage management in data centers [29].

Distributed UPS Systems. Uninterruptible power supplies (i.e., UPS devices) offer efficient peak power shaving in data centers [15] [13] [8]. For example, Google data centers employ server-level UPS units, after which a battery is attached on each server [30]. Urgaonkar *et al.* proposed the usage of UPS units to offer ample opportunities of cost reduction in data centers [31], by first prove the feasibility of leveraging energy storage device (e.g., lead-acid batteries) in data centers to reduce peak power cost. Aksanli *et al.* applied distributed UPS devices to store energy during low load activity periods while using UPS stored energy during power spikes [15]. Kontorinis *et al.* explored the total cost of operation of the distributed UPS system in datacenters and proposed using local distributed UPS systems to shave the datacenter's peak power [13]. Govindan *et al.* designed a UPS-based energy buffer to reduce energy costs in data centers [30]. To better utilize the temporal variation of electricity prices, Wang *et al.* deployed UPS systems to shift demand peak away from high-price periods in data centers [32]. Unlike the aforementioned techniques, REDUX stores energy in UPS units during intervals when renewable energy is stable and incessant or power grid prices are low.

III. Framework Design

We start this section by depicting the REDUX system framework (see Section III-A), which offers a high-level design from the perspective of power management in data centers. Next, we shed light on the responsibilities of the core modules in REDUX (see Section III-B).

A. The REDUX Platform

REDUX is a management system orchestrating UPS units and renewable energy for computing servers according to workload requirements in data centers. In what follows, we outline the correlations between REDUX and the external entities (e.g., renewable energy), followed by the descriptions of the primary modules in REDUX.

Fig. 1 plots the framework design of the REDUX system, where renewable energy (e.g., wind and solar), grid power, and diesel generators are seamlessly integrated (see the left-hand side of Fig. 1). REDUX employs a distributed UPS system, where a UPS device is attached to each server rack (see the right-hand side of Fig. 1).

REDUX persistently communicates with the five external entities, namely, renewable energy supplies, a power grid, UPS units, server racks and workload requirements. A wide range of energy supplies may include, but is not limited to, wind and solar energy, an electrical grid and diesel generators. The distributed UPS system aims to buffer energy under light workload and consume the UPS energy in case of power spikes.

There are two distinctive ways of acquiring workload requirements forwarded to REDUX. First, in the batching mode, the workload requirements become available when users submit jobs to data centers. Second, in case of the interactive mode, the workload requirements are proactively and constantly monitored and predicted by data center operators. The estimated workload requirements are then considered as the trace data inputs of workload requirements,

REDUX consists of two layers : an interface layer (see all light-blue colored modules in Fig. 1) and a backbone layer (see the modules inside the light-red colored box in Fig. 1). The interface layer is comprised of four modules, including the renewable energy monitor, the grid price monitor, the UPS monitor, and the workload capability shaving module. After the workload capability shaving module retrieves workload requirements from clients, the workload information is processed and forwarded to REDUX. The backbone layer is detailed in the next subsection.

B. The Backbone of REDUX

The three core modules in the backbone layer communicate with five external entities (i.e., renewable energy supplies, a power grid, UPS units, server racks, workload requirements) through the four interface modules in the interface layer.

The backbone layer of REDUX contains three modules, namely the renewable smoothing module, the workload shaving module, and the UPS-usage update module. The algorithms of these three modules are presented in Section IV. The functionalities of the three core modules of REDUX are summarized as follows:

- **Renewable Smoothing.** The renewable smoothing module (see Algorithm 2 in Section IV.) is responsible for effectively dealing with cases where renewable energy fluctuates due to an environmental status. This module copes with the fluctuating renewable energy through a distributed UPS system.
- **Workload Shaving.** The workload shaving module is focused on treating overload conditions, in which workload exceeds the underlying data center's computing and energy capacity. This module is invoked in Steps 3 and 10 of Algorithm 1 in Section IV.
- **UPS-usage Updating.** The responsibility of the UPS-usage update module is two-fold. First, this module keeps track of the status of all UPS units in a data center. Second, the module is in control of making battery charging and discharging decisions. Refer to Algorithm 3 in Section IV for the design of the UPS-usage update module.

IV. Heuristic Algorithms

We first present a high-level control algorithm in Section IV-A. Then, Sections IV-B and IV-C shed light on the design of the smoothing and updating algorithms implemented in the backbone layer (see also Section III-B) of REDUX.

A. The High-Level Control Algorithm

We take a hierarchical design approach to the development of REDUX, in which a high-level control algorithm coordinates all the three core modules in the backbone layer (see the backbone layer in Section III-B). This subsection is dedicated to the design of the high-level controller, whereas the subsequent subsections articulate the algorithms of the core modules, namely, renewable energy smoothing and UPS-usage updating (see also Sections IV-B and IV-C).

Algorithm 1 depicts the pseudo-code of the high-level algorithm in REDUX. The high-level coordinator kicks off the power management task with the workload-shaving procedure (see Line 3).

Algorithm 1 The high-level control algorithm in REDUX.

Input:
Renewable energy states $S_{RE} = \{STA, FLU, OTA\}$
Workload State $S_w = \{OVR, OFP\}$
Energy demand from workload during time t, W_t
Output:
Redux Cost of All Energy

1: $t = 0$
2: **while** $t <= T$ **do**
3: $workload\_shaving()$; /* with workload capability */
4: $update\_ups\_utilitylevel()$;
5: **if** $S_{RE} = FLU$ **then**
6: $ren\_supply\_smooth()$;
7: **end if**
8: $estimate\_overpeak\_level()$;
9: **if** $(S_w = OVR)$ **then**
10: $workload\_shaving()$;
11: /* with estimated overpeak workload */
12: **end if**
13: $update\_ups\_supply()$;
14: $E_t^G = W_t - E_t^{RE} - E_t^{UPS}$
15: $calculate\_energy\_cost()$;
16: $t{+}{+}$
17: **end while**
18: **return** Redux cost

The purpose of workload shaving is the overloading of a data center with respect to power supplies and computing capacity. More specifically, if the submitted load is below the overloading threshold, the pending jobs will be immediately processed in the current time slot. Otherwise, these jobs will be queued and delayed by the high-level controller. Jobs resulting in overload should be scheduled and processed in the subsequent time slots. It is note worthy that scheduling such jobs under the overloading condition imposes significant impact on the data center's overall performance metrics such as throughput and response time. The investigation of scheduling policies in the overloading case is out of scope of this study. We intend to address this concern as a future research direction.

The procedure of updating UPS utility levels (see $update\_ups\_utilitylevel()$ in Line 4) aims to protect UPS units against frequent charging and discharging, thereby prolonging lifetime of the distributed UPS system. This procedure determines a UPS energy level under which the UPS units should be protected. Such levels largely depend on current workload conditions as well as required energy capacity.

If the renewable energy is in the fluctuation state, the renewable-energy-supply smoothing policy is invoked in Line 5 of Algorithm 1. The smoothing procedure is governed by the current renewable supply, a stable energy supply level, and a UPS energy level.

Line 8 (see also $estimate\_overpeak\_level()$) of the high-level control algorithm is dynamically and approximately project a peak workload level. Such estimation is accomplished by providing the information pertaining to the current workload, renewable supply, UPS energy level and electricity price.

If the workload exceeds the peak level (see Line 9), then the workload-shaving procedure is kicked in to defer the extra load to the next time slots (see Line 10).

The functionality of Line 13 (see $update\_ups\_supply()$ in the top-level controller is two-fold: (1) updating the UPS status information and (2) making UPS discharging and charging decisions.

After Line 14 computes the energy supply from the electrical grid, Line 15 calculates the energy cost. The $calculate\_energy\_cost()$ function enables us to quantitatively compare REDUX against two exiting power management strategies (see also Section V).

B. Smoothing Renewable Energy Supplies

Recall that Step 6 in Algorithm 1 is a smoothing operation for renewable energy supplies. This operation is dedicated to smooth renewable energy output for data centers.

Algorithm 2 Smoothing Renewable Energy Supplies

Input:
grid price P^G, and state S_{GP}
renewable price P^{RE}, renewable supply E^{RE}
stable renewable supply E^{STA}
Output:
updated renewable supply $\bar{E}^{RE}$
updated UPS energy storage $\bar{E}^{UPS}_{storage}$

```
1: if E^RE < E^STA then
2:    if S_GP = HIGH then
3:       Discharge UPS units to offer stable renewable supply;
4:    else
5:       Use the power grid for smoothing;
6:       if P^G < P^RE then
7:          Recharge the UPS units;
8:       end if
9:    end if
10: else
11:    Recharge the UPS units using renewable energy;
12:    Use renewable energy to power servers;
13: end if
```

Algorithm 2 outlines the pseudo-code of the smoothing operation. If the renewable energy supply is lower than the stable threshold (i.e., see $E^{RE} < E^{STA}$ in Line 1), the renewable energy output fluctuates due to renewable resource variations. In such a fluctuation case, energy should be supplemented by the underlying UPS systems (see Lines 2-3) or the power grid (see Lines 5-8). Specifically, when the price of the electricity grid is high, the UPS units discharge and supply energy to the servers (see Line 3). In case the power grid offers cheap energy, REDUX fully utilizes the grid to smooth the renewable energy supply (see Line 5). It is economically wise to recharge the UPS system using the power grid at cheap price (see Line 7). When the renewable resources are abundant, the UPS devices are recharged by the renewable energy (see Line 11). Further, the servers will be powered by cost-effective renewable energy if the renewable energy generation is sufficient (see Line 12).

C. Updating UPS Energy Supply

Now we delineate an algorithm for update UPS energy supplies. This algorithm is invoked in Step 13 in Algorithm 1 (see Section IV-A. The updating-UPS algorithm keeps track of the status of the UPS energy supply (i.e., E^{UPS}).

Algorithm 3 Updating UPS Energy Supply

Input:
Renewable energy states, $S_{RE} = \{STA, FLU, OTA\}$
Grid price states, $S_{GP} = \{HIGH, LOW\}$
Energy demand from workload during time t, W_t
estimated overpeak workload, W_{OVR}
UPS energy dis/recharged during $smoothing()$, ΔE^{UPS}
Output:
UPS supply E^{UPS}

```
1: if S_RE = OTA then
2:    if W_t >= W_OVR and S_GP = HIGH then
3:       Discharge UPS units;
4:    end if
5:    if W_t < W_OVR and S_GP = LOW then
6:       recharge UPS until full
7:    end if
8: end if
9: if S_RE = FLU then
10:    if W_t < W_OVR and S_GP = LOW then
11:       Recharge the UPS units;
12:       Update the UPS supply with ΔE^UPS;
13:    end if
14: end if
15: if S_RE = STA then
16:    if S_GP = LOW or (W_t < W_OVR and S_GP = HIGH) then
17:       Recharge the UPS units while renewable energy is accessible;
18:    end if
19: end if
```

Algorithm 3 illustrates the procedure of updating UPS energy information. The algorithm updates the UPS energy supply under three distinctive renewable-energy conditions, namely, the outage (see Lines 1-8), fluctuation (see Lines 9-14), and stable state (see Lines 15-19). If a renewable energy outage occurs, energy must be supplied by either the power grid or the distributed UPS system.

REDUX chooses to discharge the UPS units if the current workload is high and the power price from the grid is expensive (see Lines 2-3); the UPS devices are recharged when the grid price becomes cheap (see Lines 5-6).

When the renewable energy resource is in the fluctuation state and the current workload is below the peak level, the UPS units are recharged by cheap power grids (see Lines 10-11).

In case of abundant renewable energy resources (i.e., $S_{RE} = STA$), REDUX decides to recharge the UPS units under one of the two conditions: (1) the power price of the grid is fairly low or (2) current workload is in the off-peak window and the power grid price is high (see Lines 16-17).

V. Results and Analysis

In this section, we evaluate the performance of REDUX driven by real-world renewable energy and power grid price data. We compare REDUX with a baseline solution called *noREDUX* as well as two existing power management techniques - *GreenSwitch* [12] and *ReUPS* [8]. We measure the accumulated energy cost of a simulated data center governed by REDUX, noREDUX GreenSwitch, and RE-UPS under various conditions.

Before presenting experimental results, let us discuss the experimental settings in Section V-A.

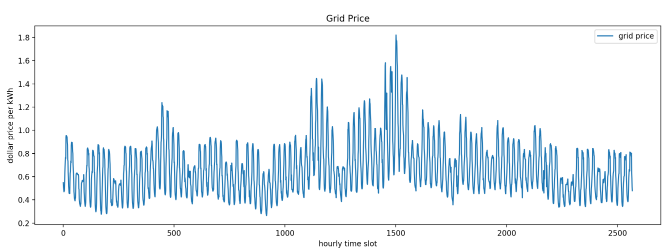

Figure 2. The electricity price of a power grid in the New York state during the period of three month ranging from June 1 to August 31, 2006. Unit: $\times$100$/MWh

A. Experimental Settings

In our experiments, we test REDUX and its competitors using the electricity price of a real-world power grid in New York state during a period of three months from June 1 to August 31, 2006. We pay attention to this time period, because the solar data was collected during this period. Fig. 2 shows that the power grid price dynamically changes during the three-month time interval, where three noticeable price peaks occur at around 480, 1200, and 1500 hours. The maximum and minimum prices in the trace are 182 and 26 $/MWh, respectively.

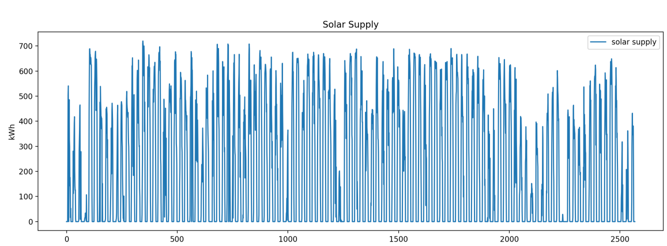

Figure 3. The solar supply of New York state during the three-months period ranging from June 1 to August 31, 2006.

From the National Renewable Energy Laboratory's (NREL) database, we retrieve the solar supply of New York state during the three-month period from June 1 to August 31, 2016. The solar supply data measured in KWh is plotted in Fig. 3. The solar and wind power price is set at $0.09/KWh and $0.07/KWh, respectively. When it comes to the UPS devices, the energy cost for recharging and discharging batteries is set to $0.07/kWh.

B. REDUX vs. noREDUX

In the first experiments, we compare REDUX with noREDUX - a baseline power manager where renewable energy resources and UPS units are not incorporated.

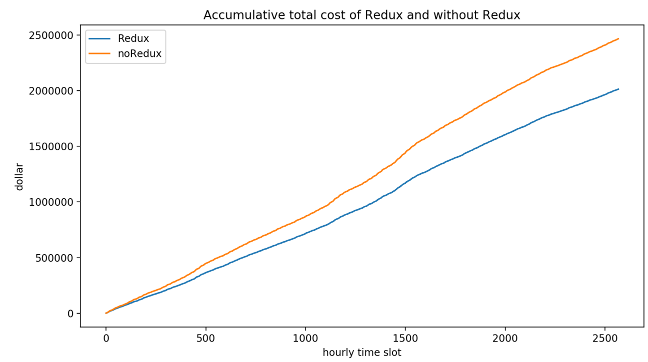

Figure 4. REDUX significantly reduces the energy cost of a data center managed by noREDUX - a traditional scheme.

Fig. 4 reveals the energy-cost comparison between REDUX and noREDUX. Regardless of REDUX or noREDUX, the cumulative energy cost linearly increases with time. The results show that REDUX significantly cut back the energy of the data center governed by noREDUX. For example, REDUX is able to reduce the energy cost of noREDUX by 32.6% by the end of the first month; such cost savings becomes 27.7% and 24.0% by the end of the second month and third month, respectively.

The energy-cost savings are expected because REDUX orchestrates renewable energy resources and UPS units to conserve energy cost when the electricity price of the power grid is expensive. For example, there are multiple sharp peaks (e.g., see 480, 1200, and 1500 hours in Fig. 2) in the grid price trace data. REDUX makes judicious decisions to power the data center using either renewable energy or the distributed UPS system rather than the expensive power grid.

C. Improving GreenSwitch and ReUPS

Now we compare REDUX with the two existing schemes - GreenSwitch and ReUPS. Fig. 5 shows the cumulative energy cost of the data center managed by REDUX, GreenSwitch, and ReUPS, respectively. Like the trend plotted in Fig. 4, the energy cost of the three management schemes grows with time.

More importantly, Fig. 5 illustrates that REDUX noticeably outperforms GreenSwitch and ReUPS in terms of energy cost. For instance, by the end of the first month, REDUX slashes

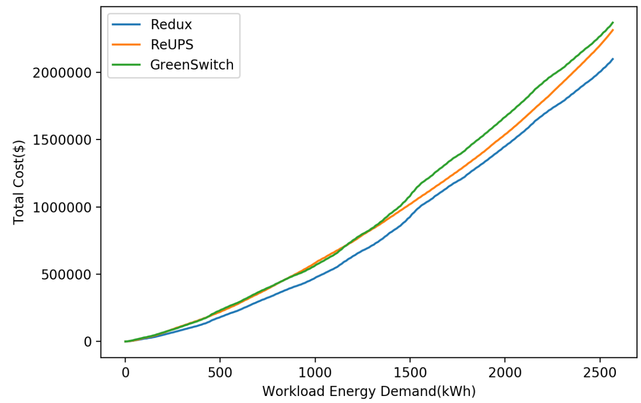

Figure 5. REDUX significantly reduces the energy cost of a data center managed by noREDUX - a traditional scheme.

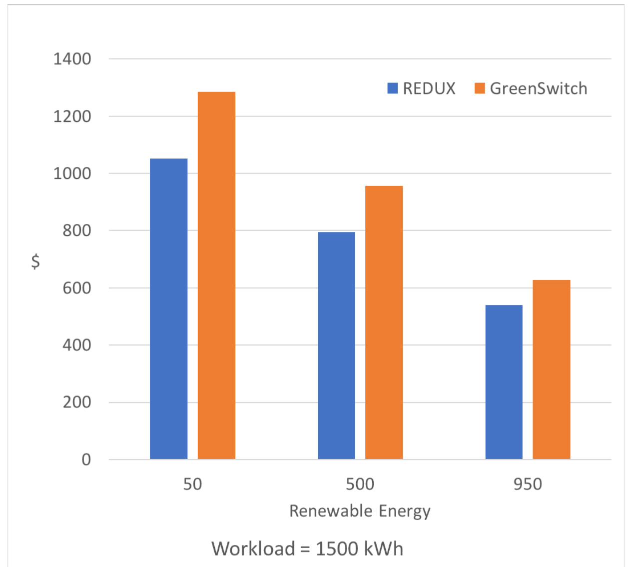

Figure 6. The impacts of renewable energy supply on energy cost of REDUX and GreenSwitch when the workload is set to 1500.

the energy cost of GreenSwitch and ReUPS by 15.5% and 16.7%, respectively; by the end of the second month, REDUX reduces the energy cost of GreenSwitch and ReUPS by 12.3% and 9.5%, respectively; such cost savings becomes 10.6% and 5.7% by the end of the second month and third month, respectively. Table II summarizes the cumulative energy cost of the three management strategies by the end of the first, second, and third month, respectively. The energy-cost saving rates of REDUX over GreenSwitch and ReUPS can also be found in Table II.

REDUX is superior to GreenSwitch, because REDUX makes use of the distributed UPS system to smooth renewable energy supply. The improvement of REDUX over ReUPS is ascribed to the awareness of changing power grid price. REDUX makes full advantage of renewable energy coupled with the UPS devices to offer energy supply when the power grid price becomes high (see, for example, multiple sharp peaks in Fig. 2). When the power grid price is surgeing, REDUX switches power supply from the grid to either renewable energy resources or the UPS system, depending on current workload conditions.

D. Impacts of Renewable Energy

In the last experiment, we investigate the impact of renewable energy level on the performance of REDUX and GreenSwitch. The performance of ReUPS is close to that of REDUX in this experiment and; therefore, we ignore the results of ReUPS in this subsection. Fig. 6 shows the energy cost of REDUX and GreenSwitch when the renewable energy supply is set at the levels of 50, 500 and 950 kWh. The results suggest that when the renewable energy level increases from 50 to 500, the overall energy cost of the data center is cut back significantly. Unfortunately, when the renewable energy level increases further to 950, there is no noticeable reduction in energy costs. When the renewable energy level is 50, energy costs of REDUX is much lower than that of GreenSwitch thanks to the adoption of UPS units in REDUX.

VI. Conclusions and Future Work

In this paper, we presented a resource manager called *REDUX* to on-site renewable sources like solar coupled with a distributed UPS system to reduce energy cost of data centers. REDUX orchestrates UPS units to judiciously cope with the intermittency nature of renewable energy integrated with power grids. REDUX makes critical decisions on UPS charging and discharging with sufficient information on renewable-energy supply levels and time-dependent grid power prices. More specifically, REDUX makes prudent discharge of batteries to offer energy resources when renewable energy production is low or in the fluctuate condition. REDUX makes judicious decisions to charge batteries when renewable energy levels are high coupled with low loads.

One salient feature of REDUX is to effectively slash energy costs of data centers powered by both renewable and conventional energy. Compared with the prior solutions, REDUX delivers a prominent capability of mitigating average peak workload and boosting renewable-energy utilization. The experimental results demonstrate that REDUX paves the way for constructing modern data centers that are economically and environmentally friendly.

There are two future research directions. First, we will unravel a plan to explore scheduling policies during peak load. We expect that the scheduling policies undoubtedly have a tremendous impact on energy efficiency and performance of data centers. Second, the smoothing algorithm implemented in REDUX is a pilot study towards optimizing renewable energy. To extend the smoothing algorithm, we intend to propose a predictive scheme to make judicious smoothing decisions on renewable energy supplies.

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Table II. Cumulative energy-cost comparisons among REDUX, GreenSwitch, and ReUPS the end of the first, second, and third month.

Power Management	1st Month	1st Month Reduction Rate	2nd Month	2nd Month Reduction Rate	3rd Month	3rd Month Reduction Rate
REDUX (This Study)	$322,203.5	N/A	$912,613.5	N/A	$1,693,150.5	N/A
GreenSwitch [12]	$386,708.9	16.7%	$1,008,770.3	9.5%	$1,796,271.6	5.7%
ReUPS [8]	$381,279.2	15.4%	$1,040,413.2	12.2%	$1,894,644.1	10.6%

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