



Ecovisor: A Virtual Energy System for Carbon-Efficient Applications

Abel Souza

University of Massachusetts Amherst
USA

Noman Bashir

University of Massachusetts Amherst
USA

Jorge Murillo

University of Massachusetts Amherst
USA

Walid Hanafy

University of Massachusetts Amherst
USA

Qianlin Liang

University of Massachusetts Amherst
USA

David Irwin

University of Massachusetts Amherst
USA

Prashant Shenoy

University of Massachusetts Amherst
USA

ABSTRACT

Cloud platforms' rapid growth is raising significant concerns about their carbon emissions. To reduce carbon emissions, future cloud platforms will need to increase their reliance on renewable energy sources, such as solar and wind, which have zero emissions but are highly unreliable. Unfortunately, today's energy systems effectively mask this unreliability in hardware, which prevents applications from optimizing their carbon-efficiency, or work done per kilogram of carbon emitted. To address the problem, we design an "ecovisor," which virtualizes the energy system and exposes software-defined control of it to applications. An ecovisor enables each application to handle clean energy's unreliability in software based on its own specific requirements. We implement a small-scale ecovisor prototype that virtualizes a physical energy system to enable software-based application-level i) visibility into variable grid carbon-intensity and local renewable generation and ii) control of server power usage and battery charging and discharging. We evaluate the ecovisor approach by showing how multiple applications can concurrently exercise their virtual energy system in different ways to better optimize carbon-efficiency based on their specific requirements compared to general system-wide policies.

CCS CONCEPTS

• **Computer systems organization** → **Cloud computing; Special purpose systems.**

KEYWORDS

Sustainable computing, operating systems, cloud computing

ACM Reference Format:

Abel Souza, Noman Bashir, Jorge Murillo, Walid Hanafy, Qianlin Liang, David Irwin, and Prashant Shenoy. 2023. Ecovisor: A Virtual Energy System

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

ASPLOS '23, March 25–29, 2023, Vancouver, BC, Canada

© 2023 Association for Computing Machinery.

ACM ISBN 978-1-4503-9916-6/23/03...\$15.00

<https://doi.org/10.1145/3575693.3575709>

for Carbon-Efficient Applications. In *Proceedings of the 28th ACM International Conference on Architectural Support for Programming Languages and Operating Systems, Volume 2 (ASPLOS '23), March 25–29, 2023, Vancouver, BC, Canada*. ACM, New York, NY, USA, 14 pages. <https://doi.org/10.1145/3575693.3575709>

1 INTRODUCTION

Cloud platforms are growing exponentially, and have been for some time, with a recent analysis estimating a $6\times$ increase in their capacity from 2010-2018, or roughly a 22.4% increase per year [51]. This "hyperscale" growth is being driven by the continual development of new and useful, but often computationally-intensive, applications, particularly in artificial intelligence (AI) and machine learning (ML) [22]. As they have grown, to mitigate large increases in their energy consumption and cost, cloud platforms have aggressively optimized their energy-efficiency, e.g., by reducing their power usage effectiveness (PUE) – the ratio of total datacenter power to server power – to near the optimal value of 1 [11, 18].

However, further improving energy-efficiency is becoming increasingly challenging, as it is already highly optimized. Thus, continued growth in cloud capacity will likely result in much larger increases in energy consumption moving forward. Of course, this energy growth is also increasing cloud platforms' carbon and greenhouse gas (GHG) emissions, which are causing the Earth's temperature to rise [40, 52]. The negative environmental effects of cloud platforms' hyperscaler growth have begun to receive significant attention. As a result, all the major cloud providers have announced aggressive goals for reducing, and ultimately eliminating, their platforms' carbon emissions over the next decade, while acknowledging that many of the technologies necessary to achieve these sustainability goals have yet to be developed [1, 20, 31, 54, 65].

Ultimately, reducing cloud platforms' carbon emissions will require them to power their cloud and edge datacenters using cleaner "lower-carbon" energy sources. A distinguishing characteristic of clean energy is its unreliability: it is intermittent and not available in unlimited quantities at any single location all the time. Notably, clean energy's unreliability manifests itself in two distinct ways within our current energy system: i) the unreliability of renewable power generation and ii) the volatility of grid power's carbon-intensity. In the former case, the power generated by zero-carbon renewable energy sources, primarily solar and wind, at any location

is unreliable because it varies based on changing environmental conditions. In the latter case, the carbon-intensity of grid power — in $\text{kg}\cdot\text{CO}_2$ equivalent per watt (W) — is volatile because it varies based on the carbon emissions of the different types of generators the electric grid uses to satisfy its variable demand. As we discuss, both forms of unreliability are important to consider in reducing cloud platforms' carbon emissions.

Compared to other industries, computing is uniquely well-positioned to reduce its carbon emissions by transitioning to cleaner energy sources, despite their unreliability, for numerous reasons. Most importantly, computation often has significant spatial, temporal, and performance flexibility, which enables shifting the location, time, and intensity of its execution to better align with the availability of low-carbon grid power and zero-carbon renewable power [33, 34, 62]. In addition, computation can also leverage numerous software-based fault-tolerance techniques, including checkpointing, replication, and recomputation, to continue execution despite unexpected variations in the availability of low-carbon energy, which may require throttling or shutting down servers [64].

Unfortunately, today's cloud applications cannot leverage the unique combination of advantages above to optimize their *carbon-efficiency*, or work done per kilogram (kg) of carbon (and other GHGs) emitted, because current energy systems effectively mask clean energy's unreliability from them in hardware. That is, energy systems have traditionally and implicitly exposed a *reliability abstraction* — the abstraction of a reliable supply of power on demand up to some maximum — to electrical devices, including servers, via their electrical socket interface. Of course, in many cases, the energy system now includes a connection to not only the grid, but also an increasingly rich local energy system that may include substantial energy storage, e.g., batteries [56], and co-located renewable energy sources, e.g., wind and solar [44]. Since energy systems hide their increasing complexity behind the reliability abstraction, they provide applications no control of, or visibility into, the characteristics of their energy supply, i.e., its consumption, generation, or carbon emissions. Thus, applications cannot optimize carbon-efficiency by regulating their power usage to respond to changes in grid power's carbon-intensity and renewable power's availability.

To address the problem, this paper presents the design and implementation of an *ecovisor*—a software system that exposes software-defined control of a virtual energy system directly to applications. An *ecovisor* is akin to a hypervisor but virtualizes the energy system of computing infrastructure instead of virtualizing the computing resources of a single server. Importantly, an *ecovisor* enables applications to handle clean energy's unreliability within their software stack based on their own specific characteristics, performance requirements, and sustainability goals by leveraging one or more dimensions of software flexibility and software-based fault-tolerance. *Ecovisors* also enable applications to exercise software-based control of their virtual energy system to mitigate clean energy's unreliability. Specifically, instead of temporally or spatially shifting their computing workload, applications can control their virtual battery to temporally shift their clean energy usage—by storing renewable or low-carbon grid energy when it is available for later use.

In some sense, our approach extends the end-to-end principle [61] to the energy system by i) recognizing that the energy

system's current reliability abstraction prevents designing carbon-efficient applications, and ii) addressing the problem by pushing control of the energy system from hardware into software. Our approach is also inspired by the exokernel argument from operating systems that advocates delegating resource management to applications [30, 42]. Our *ecovisor* extends this approach by delegating not only resource management to applications, but also management of the energy (and carbon) that powers those resources. Our hypothesis is that exposing software-defined visibility and control of a virtualized energy system enables applications to better optimize carbon-efficiency based on their specific characteristics and requirements compared to general system policies. In evaluating our hypothesis, this paper makes the following contributions.

Virtualizing the Energy System. We present our *ecovisor* design, which virtualizes a physical energy system to enable software-based control of server power consumption and battery charging/discharging, as well as visibility into variable grid carbon-intensity and renewable generation. In particular, our *ecovisor* exposes a software API to applications that enables them to control their use of power to respond to uncontrollable variations in grid power's carbon-intensity and renewable power's availability.

Carbon-Efficiency Optimizations. We present multiple case studies showing how a range of different applications can use the *ecovisor* API to optimize their carbon-efficiency. Our case studies highlight two important concepts including: i) different applications use their virtual energy system in different ways to optimize carbon-efficiency, and ii) application-specific policies can better optimize carbon-efficiency compared to general one-size-fits-all system policies. While optimizing energy-efficiency has been well-studied in computing, there has been little research on optimizing carbon-efficiency, which is both fundamentally different and the only metric that really matters for addressing climate change.

Implementation and Evaluation. We implement a small-scale *ecovisor* prototype on a cluster of microservers that exposes a virtual grid connection, solar array, and batteries to applications. We evaluate our prototype's flexibility by concurrently executing the case study applications above, and showing that optimizing their carbon-efficiency on a shared infrastructure requires application-specific policies. For example, an interactive web service may use carbon budgeting to maintain a strict latency SLO as carbon-intensity varies, while a parallel batch job might instead adjust its degree of parallelism. We release our *ecovisor* prototype as an open-source tool that can be used by researchers and practitioners in developing carbon optimizations: github.com/carbonfirst/ecovisor

2 MOTIVATION AND BACKGROUND

Motivation. In general, sustainable computing focuses on the design and operation of carbon-efficient computing infrastructure and applications. This paper focuses on reducing Scope 2 operational carbon (and other GHG) emissions from using electricity [12], which represents a significant fraction of cloud platforms' emissions. Optimizing Scope 1 direct emissions and Scope 3 embodied emissions are outside our scope. While these other classes of emissions are also important, cloud platforms have few Scope 1 emissions, and have no direct control over their Scope 3 emissions.

While cloud platforms have long focused on optimizing energy-efficiency, optimizing carbon-efficiency is fundamentally different.

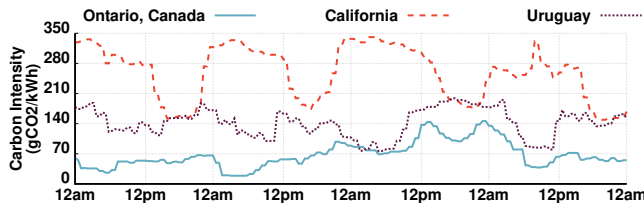


Figure 1: Grid carbon emissions for three different regions showing spatial and temporal variations.

To illustrate, consider that a highly energy-efficient system can be highly carbon-inefficient if its grid-supplied power derives from burning fossil fuels, while a highly energy-inefficient system can be highly carbon-efficient if its power derives solely from zero-carbon renewable energy. As this trivial example shows, a cloud platform’s carbon-efficiency depends, in part, on the carbon-intensity of its energy supply, which varies over time based on variations in both grid power’s carbon-intensity and local renewable power’s availability.

Since modifying a cloud platform’s operations to adapt to variations in carbon-intensity, e.g., by throttling workloads when carbon-intensity is high, is challenging, cloud providers have largely focused on transparently reducing their *net* carbon emissions using *carbon offsets*. Such offsets are an accounting mechanism that enables offsetting the direct use of carbon-intensive energy by purchasing zero-carbon renewable energy generated at another time and location [43, 58]. Carbon offsets are attractive because they do not require complex operational changes to reduce net carbon emissions. Many prominent technology companies have eliminated their net carbon emissions [1, 31, 54, 65], which they often refer to as running on “100% renewable energy.” Unfortunately, carbon offsets do not reduce direct carbon emissions, and become increasingly less effective as carbon emissions decrease, as there is less carbon left to offset. In contrast, eliminating *absolute* carbon emissions will ultimately require cloud platforms to change their operations to reduce their direct carbon emissions by better aligning their computing load with when and where low-carbon energy is available.

Reducing direct carbon emissions is challenging largely because it introduces a new constraint that requires users to voluntarily making difficult tradeoffs between performance/availability, cost, and carbon emissions. In general, modifying applications’ design and operation to reduce their direct carbon emissions decreases their performance/availability, while also increasing cost, as energy prices do not (yet) incorporate the cost of carbon’s negative externalities to the environment. Importantly, the optimal tradeoff between performance/availability, cost, and carbon emissions differs across applications and users. As we show in §5, the policies for reducing the carbon emissions of delay-tolerant batch applications are significantly different from those for interactive web services, which often must adhere to a strict latency Service Level Objective (SLO). More generally, though, cloud users, i.e., companies, have widely different goals, strategies, and tolerances for reducing carbon (at the expense of increased cost and lower performance/availability), which cloud platforms do not know. As a result, cloud platforms are not well-positioned to manage carbon emissions at the system-level on behalf of their users, which motivates our ecovisor’s approach of exposing energy and carbon management to applications.

The motivation for our ecovisor’s application-level control of carbon is analogous to that for cloud auto-scaling: all cloud platforms support elastic auto-scaling that enables applications to horizontally or vertically scale their resources in response to variations in their workload’s intensity [3, 14]. These auto-scaling policies are application-specific for similar reasons as above, i.e., differing application requirements and user tradeoffs between cost and performance/availability. Our ecovisor’s API, discussed in §3, enables similar “auto-scaling” but in response to variations in grid power’s carbon-intensity and local renewable energy’s availability. A simple evolutionary path to enabling such “carbon-scaling” using an ecovisor is to augment existing cloud auto-scaling APIs. For example, existing APIs, such as Amazon CloudWatch [37] and Azure Monitor [4], already expose visibility into platform resource usage, and could easily be extended to include power and carbon information. In this case, cloud platforms would “delegate” carbon-scaling to applications just as they currently delegate auto-scaling resources.

While the ecovisor approach could apply to existing cloud platforms, especially those hosted at datacenters with substantial co-located renewables [44] and energy storage [59], there is currently no financial incentive to reduce carbon. This is a social problem, not a technical one. In the end, to halt climate change, government policies will likely be necessary to create strong incentives for monitoring and reducing carbon emissions, either directly, e.g., via carbon caps, or indirectly, e.g., via carbon pricing or other incentives. Nevertheless, cloud platforms have already begun to expose visibility into their carbon emissions [10], driven by their customers’ increasing desire to measure and report carbon emissions data. This combination of customer demand and government policy is likely to incentivize future cloud platforms to adopt ecovisor-like mechanisms for measuring and controlling carbon emissions.

Background. Our work assumes a datacenter’s physical energy system connects to up to three distinct power sources: the electric grid, local batteries (or other forms of energy storage), and local renewable generation, such as solar or wind. The power supplied to the servers (and other computing equipment) is a mix of these three power sources. Not all facilities will have connections to all three power sources, and the capacity of each source may vary. For example, many large cloud datacenters may not have local renewables, while smaller edge sites might not require a grid connection, i.e., if they have enough local renewables and battery capacity to be self-powered [34]. Importantly, an ecovisor requires software-defined monitoring and control of both server power and the physical energy system, i.e., power’s supply, demand, and carbon emissions.

Monitoring Power. An ecovisor must be capable of monitoring each energy source’s power generation and consumption. Energy system components commonly expose power monitoring via programmatic APIs. For example, battery charge controllers, such as Tesla’s Powerwall, support querying a battery’s energy level, and its charge/discharge rate from the grid and solar [15], while solar inverters support querying current and historical solar power generation [15]. Our ecovisor builds on these existing APIs. An ecovisor must also be capable of monitoring server power consumption. Most servers include power monitoring functions internally, e.g., in hardware exposed to the OS, or externally, e.g., via IPMI [13].

Monitoring Carbon. An ecovisor must be capable of monitoring grid power’s carbon-intensity in real time. Recently, third-party

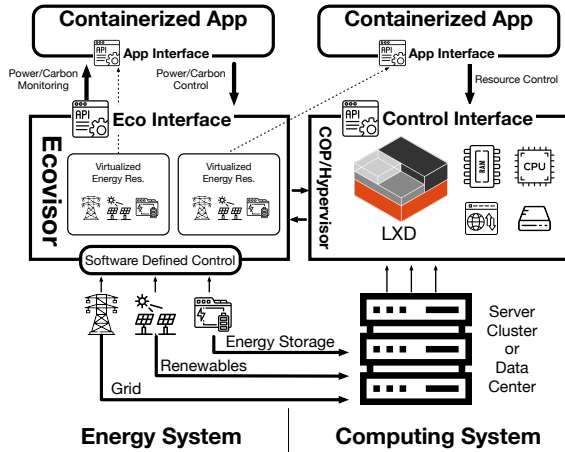


Figure 2: Our ecovisor’s design uses containers (or VMs) for resource, energy, and carbon management.

carbon information services, such as electricityMap [9] and Watt-Time [19], have begun providing real-time, location-specific estimates of grid power’s carbon-intensity by tracking the output of each grid generator, and estimating its carbon emissions based on the type of generator. Cloud platforms are now using these services to provide coarse-grained estimates of each region’s average carbon-intensity [8]. Instead, our ecovisor uses these APIs to monitor fine-grained grid carbon-intensity, e.g., every 5 minutes. Figure 1 shows how grid power’s carbon-intensity varies over time at different locations. As shown, Ontario has the lowest carbon-intensity due to its use of nuclear power, while Uruguay has a slightly higher carbon-intensity due to its use of hydroelectricity. California has the highest carbon-intensity due to the use of fossil fuels, but also the highest variability due to its high solar penetration.

Controlling Power. Finally, our ecovisor must be capable of controlling power usage in response to changes in grid power’s carbon-intensity and renewable energy availability, including regulating server power consumption and battery charging/discharging, i.e., by enabling software to cap the maximum power discharged from batteries and regulate when and how much to charge batteries from the grid and renewables. In the former case, there has been significant prior work on power capping servers and containers by limiting their resource usage [48, 63]. Our ecovisor leverages these software-based techniques to cap per-container power. Specifically, our prototype takes a similar approach as recent work [48], which caps container power by limiting the utilization per core. In the latter case, battery charge controllers often do not expose control functions to software, since they implement the reliability abstraction, which never artificially caps power and always charges grid-connected batteries to full capacity. However, recently, battery management systems, such as Tesla’s Powerwall, have begun to expose these functions in software, which our ecovisor leverages [17].

3 ECOVISOR DESIGN

Figure 2 provides an overview of our ecovisor’s general design, which uses containers or virtual machines (VMs) as the basic unit of resource allocation and energy management. We chose a container/VM instance-level API, in part, because it aligns with, and

could easily extend, existing instance-level cloud APIs. As we discuss, an instance-level API can also support higher-level cluster or cloud-level APIs that provide simplified abstractions for specific types of applications, such as geo-distributed applications.

An ecovisor integrates with and extends an existing orchestration platform that already provides basic container (or VM) management and monitoring functions, including creating and destroying containers (or VMs), as well as allocating resources to them. Note that Container Orchestration Platforms (COPs), such as Kubernetes and Mesos, and similar VM orchestration platforms, generally do not provide sophisticated fine-grained energy monitoring and management functions. As discussed in §4, our implementation specifically builds on LXD [50], which is a simple COP that exposes basic container management functions over a REST API, similar to Kubernetes and Mesos. We chose to extend a COP for our prototype because these platforms have become the *de facto* operating systems for uniformly managing the resources of large server clusters. However, while we focus our discussion below on COPs, our design also applies to similar platforms that orchestrate VMs.

COPs provide distributed applications with the abstraction of their own virtual cluster composed of multiple containers, each with a specified resource allocation. These virtual clusters are elastic, such that the number of containers and each container’s allocated resources may grow or shrink over time based on application demand and resource availability. In particular, applications may *horizontally scale* their number of allocated containers as demand changes, or *vertically scale* the resources allocated to each container. COPs include a scheduling policy that determines how to allocate resources to applications under constraint. There are many possible resource scheduling policies that optimize for different objectives, such as fairness, e.g., Dominant Resource Fairness [32], or revenue, e.g., cloud spot markets [2, 5]. These policies may require the scheduler to reclaim (or revoke) resources from distributed applications. As a result, distributed applications that run on COPs are already designed to be resilient to resource revocations. As we discuss, this resiliency is also useful for designing carbon-efficient applications, since the unreliability of low-carbon energy may cause power shortages that also manifest as resource revocations.

3.1 Extending COPs with an Ecovisor

Virtual Energy System. An ecovisor extends COPs’ existing API to provide the abstraction of a virtual energy system, which supplies power to each application’s virtual cluster. As shown in Figure 2, our virtual energy system includes a virtual grid connection, a virtual battery, and a virtual solar array. Applications receive a share of grid power, the physical solar array’s variable power output, and the physical battery’s energy and power capacity. While our approach generally applies to wind power as well, we focus on solar because it has higher average power density and is more widely available, **Ecovisor Interface.** Table 1 shows our ecovisor’s narrow API, which is composed of three simple and basic types of methods: getters, setters, and an asynchronous notification.

Getter Methods. The getter and setter methods are synchronous downcalls. Applications use these methods for simple power and carbon monitoring, including retrieving their current virtual solar power output, grid power usage, grid power carbon-intensity, per-container power caps, and per-container power usage. As discussed

Table 1: Ecovisor’s narrow API that provides application’s visibility and control over their virtual energy system.

Function Name	Type	Input	Return Value	Description
set_container_powercap()	Setter	ContainerID, kW	N/A	Set a container’s power cap
set_battery_charge_rate()	Setter	kW	N/A	Set battery charge rate until full
set_battery_max_discharge()	Setter	kW	N/A	Set max battery discharge rate
get_solar_power()	Getter	N/A	kW	Get virtual solar power output
get_grid_power()	Getter	N/A	kW	Get virtual grid power usage
get_grid_carbon()	Getter	N/A	g·CO ₂ /kW	Get current grid carbon-intensity
get_battery_discharge_rate()	Getter	N/A	kW	Get current rate of battery discharge
get_battery_charge_level()	Getter	N/A	kWh	Get energy stored in virtual battery
get_container_powercap()	Getter	ContainerID	kW	Get a container’s power cap
get_container_power()	Getter	ContainerID	kW	Get a container’s power usage
tick()	Notification	N/A	N/A	Invoked by ecovisor every Δt

in §2, this information is readily available from the physical energy system’s components, servers, and carbon information services. Our ecovisor provides applications a uniform centralized interface to access this information, and also stores historical data in a time-series database to support sophisticated queries over historical data.

Setter Methods. Applications use the setter methods to control their virtual power’s supply and demand. Applications exercise control over their i) power demand by setting their per-container power caps and ii) power supply by determining when and how fast to charge their battery, as well as when to discharge the battery and its maximum rate of discharge. Note that the API does not include any functions for controlling virtual solar power, since it is dictated by the environment. Of course, traditional datacenters may have only grid power with no renewables or batteries. In this case, applications control their carbon emissions by explicitly setting per-container power caps to regulate grid power in response to variations in its carbon-intensity. Datacenters that have batteries may also perform carbon arbitrage, e.g., by charging their virtual batteries when carbon-intensity is low and discharging them when high, in addition to regulating their grid power usage.

When solar power is available, the ecovisor configures an application’s virtual energy system to always use virtual solar power first to satisfy demand. If there is excess solar power after meeting demand, the ecovisor automatically uses it to charge an application’s virtual battery. If an application has configured its virtual battery to charge at a higher rate than the excess solar power, then its virtual energy system supplements the charging up to the specified rate using grid power, and attributes any carbon emissions from using grid power to the application. If an application’s virtual battery fills to capacity, its excess virtual solar power must go somewhere: while resource schedulers can choose whether or not to be work-conserving, physics dictates that our virtualized energy system is energy-conserving. Determining how to handle excess solar power is a policy decision. For example, an ecovisor may reclaim excess solar energy and re-distribute it to other applications (if they have available virtual battery capacity), net meter it back to the grid (if possible), or rely on the battery charge controller to curtail it.

If there is not enough virtual solar power to meet an application’s demand, its virtual energy system first uses up to the maximum specified battery discharge rate to satisfy the deficit. If the maximum

specified battery discharge rate is still not sufficient, then the virtual energy system finally uses grid power to make up the difference, and again attributes any carbon emissions from using grid power to the application. Importantly, while grid power’s carbon-intensity, solar power, and container power usage vary continuously, our ecovisor discretizes and accounts for these values over a small discrete time (or tick) interval Δt , e.g., every minute. The virtual energy system always retains a small amount of virtual battery capacity to store the maximum solar power output over the tick interval, and accounts for this solar power output in the next interval. Thus, applications always know the solar power available in the next tick interval.

Asynchronous Notifications. An ecovisor’s virtual energy system abstraction also includes an asynchronous upcall notification based on the tick interval mentioned above. The `tick()` method is akin to an OS timer interrupt and triggers at the same tick interval over which the virtual energy system discretizes power. Applications register their `tick()` method with the ecovisor as a callback function at startup. Applications can implement sophisticated carbon management policies within their `tick()` method by examining the characteristics of their power supply, e.g., current solar power output, battery charge level, and grid power’s carbon-intensity, and their application’s characteristics, e.g., container resource utilization, power usage, and application-level performance metrics, and making adjustments to their power supply and demand to balance potentially competing objectives, such as performance, energy-efficiency, carbon emissions, and cost. Applications may also call container and resource management functions within the `tick()` method in response to changes in available solar power or grid carbon-intensity. For example, applications may horizontally scale their number of containers, or the resources allocated to each container, as solar power and grid power’s carbon-intensity vary.

There are many other external events that might require an immediate application response, which an ecovisor could also expose to applications via asynchronous upcalls. For example, a significant and sudden change in virtual solar power output or grid power’s carbon emissions, or the virtual battery reaching the full or empty state. However, since we intend the `tick()` method to execute at fine-grained intervals, e.g., every minute, applications are typically able to recognize and address these external events within their `tick()` method. In general, carbon does not change significantly

Table 2: Example library functions using ecovisor’s API.

Function Name	Description
get_container_energy()	Energy usage in interval (t_1, t_2)
get_container_carbon()	Carbon usage in interval (t_1, t_2)
get_app_power()	Power usage for an application
get_app_energy()	Energy usage in interval (t_1, t_2)
get_app_carbon()	Carbon usage for an application
set_carbon_rate()	Set carbon rate for a container
set_carbon_budget()	Set application’s carbon budget
notify_solar_change()	Called when solar changes
notify_carbon_change()	Called when grid carbon changes
notify_battery_full()	Called when battery fully charged
notify_battery_empty()	Called when battery empty

within a minute, and since our ecovisor always maintains a small amount of battery capacity to buffer solar, the battery never runs empty within a tick interval. While a virtual battery may fill up within a tick interval, it only has the potential to waste a small amount of excess solar power over the interval.

3.2 Library Interfaces

Our ecovisor’s API from Table 1 is simple and narrow by design, as it represents the minimal set of functions necessary to control power’s supply and demand. We chose a container-level API to enable the widest range of policies. Importantly, developers can use these functions to implement a range of higher-level interfaces and abstractions that simplify interactions with the virtual energy system, or make it entirely transparent to applications. For example, developers could use our container-level API to implement cluster-level carbon management policies. In addition, distributed applications that control virtual energy systems at multiple sites could implement geo-distributed policies that shift workload to the site(s) with the lowest carbon-intensity or most renewable availability. As a result, the additional complexity of using a virtual energy system need not be borne by most applications, but can instead be encapsulated in third-party software libraries and services, as with exokernels and similar library operating systems.

An ecovisor promotes innovation by enabling the development of libraries and services that implement a wide range of application-specific energy and carbon management policies. Since users and applications have widely different characteristics, goals, strategies, and tolerances for reducing carbon, which cloud providers do not know, cloud providers are not well-positioned to transparently manage energy and carbon on behalf of their users at the system-level. Table 2 depicts some simple library functions we implemented for §5’s case studies. These functions enable applications to monitor their energy usage and carbon emissions over various time intervals, both on a per-container and per-application basis, as well as specify a carbon rate or budget, such that the carbon rate dictates a threshold rate (per unit time) of carbon emissions, while a budget sets a total limit on an application’s carbon emissions.

3.3 Multiplexing the Physical Energy System

Each application’s virtual energy system exposes an API that is functionally equivalent to the underlying physical energy system. Thus, multiplexing control of the physical energy system among

applications’ virtual energy systems is straightforward, as it simply requires computing the limit on the maximum battery discharge rates and charging rates across all applications. The ecovisor has privileged access to the physical battery charge controller to set these aggregate limits. The ecovisor also has privileged access to the container management functions to set per-container power caps by setting limits on resource utilization, e.g., using cgroups. Finally, the ecovisor has privileged access to the energy and carbon monitoring services of the energy system components, e.g., battery charge controller and solar inverter, servers, and carbon information services, which it uses to perform energy and carbon monitoring and accounting for each application.

We assume an exogeneous policy determines each application’s share of grid power, the physical solar array’s variable power output, and the physical battery’s energy and power capacity. For example, public cloud platforms might sell solar and battery shares for some price independently of hardware resources. While there is also a substantial opportunity for ecovisors to dynamically vary, oversubscribe, or share energy resources among applications, similar to analogous policies for computing resources, such inter-application policies are out of our scope. Our focus is instead on enabling many different intra-application policies for optimizing carbon-efficiency.

4 PROTOTYPE IMPLEMENTATION

We first detail our ecovisor software prototype, and then describe the hardware prototype that it runs on.

Software Prototype. We implemented an ecovisor prototype using Python3 in ~2650 LOC. Our ecovisor runs on an external server and exposes a REST API to applications that includes the methods from Table 1. Applications register their `tick()` method as a callback function with the ecovisor server. Our ecovisor has privileged access to the software APIs exposed by the physical energy system’s components and the COP API for monitoring and controlling energy and server resources. While our approach is generally applicable to any COP, including Kubernetes, our prototype extends LXD [50], which is a COP that builds on LXC, the Linux container runtime. We chose LXD due to its flexibility and support for stateful applications and vertical resource scaling. LXD provisions full operating systems within containers (akin to lightweight VMs); enables vertically scaling each container’s resources using cgroups; and provides a virtual filesystem (LXCFS) mounted over `/proc` that provides accurate resource accounting for each container.

Our ecovisor wraps the LXD server, such that applications interact with our ecovisor prototype, which then proxies LXD-specific requests and responses to and from the LXD server. Our prototype relies on LXD for container management, including horizontal and vertical scaling. Our prototype uses LXD functions internally to vertically scale each container’s maximum resource allocation using cgroups to enforce per-container power caps set by the application, as in recent work [48]. We use PowerAPI [27], a toolkit for building software-defined power meters, for monitoring power, including per-container power usage, battery power usage, solar power generation, grid power usage, and grid carbon-intensity. PowerAPI stores this historical power data in a time-series database, specifically InfluxDB, which enables queries over different time intervals.

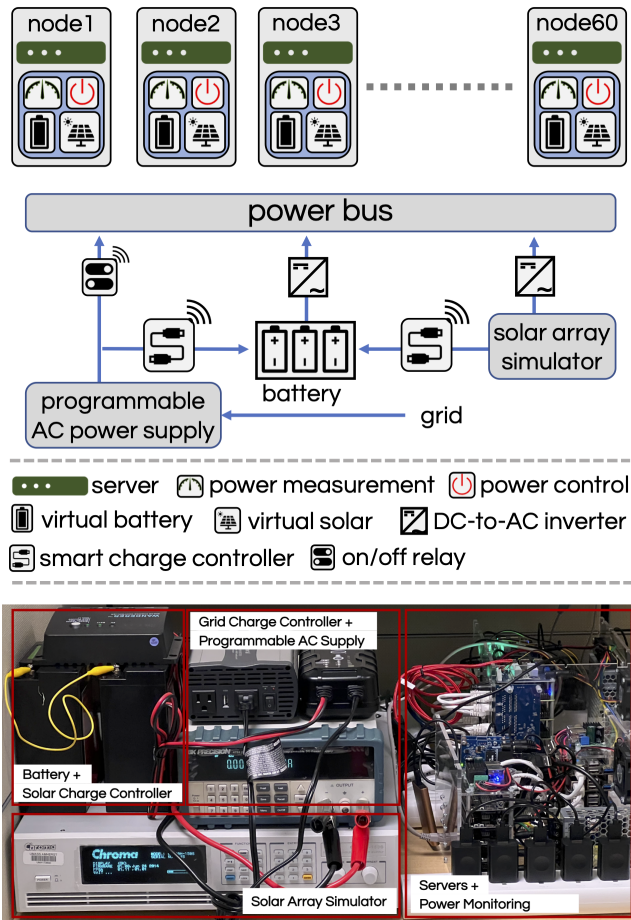


Figure 3: Overview of our prototype’s physical energy system (top), and a labeled picture of our prototype (bottom).

We use LXD’s default container scheduler, which simply allocates a container to the server with the fewest container instances.

We use electricityMap’s API to get grid power’s carbon-intensity in real-time. The implementation of other functions in our ecovisor API from Table 1 are hardware-specific. Below, we discuss the details of our hardware prototype and its energy system.

Hardware Prototype. We built a small-scale hardware prototype of a software-defined physical energy system as a proof-of-concept. Figure 3 provides an overview and picture of our hardware prototype, which is composed of a cluster of ARM-based microservers, some of which have an attached NVIDIA Jetson Nano GPU. In particular, each microserver includes a quad-core ARM Cortex A53 64-Bit processor and 4GB 1600MHz LPDDR3 memory [16] powered by a 2A, 5V power supply. The microservers consume 1.35W at idle, 5W at 100% CPU utilization, and 10W at 100% CPU and GPU utilization. The microservers run Ubuntu 18.04 Bionic minimal 64bit (arm64) with Linux kernel 4.4.2. The smart USB hubs plug into our power bus, which connects to our three power sources – the grid, battery, and solar power – discussed below. We also implemented simulated versions of each power source to enable experimentation on a more conventional datacenter server cluster composed of 16 Dell PowerEdge R430s with Intel Xeon processors with 16 cores

and 64GB memory. Implementing a real prototype at this scale is infeasible due to our lab’s power constraints, component availability, and cost. For example, the Chroma 62020H-150S, discussed below, used in our microserver prototype costs nearly \$10,000 and is only capable of emulating a solar array up to 2kW DC.

Grid Power. To validate the efficacy of our software-based power caps, we connected our system to a programmable power supply that was capable of accurately monitoring grid power consumption. We used this capability to verify that our system’s power usage never exceeded the limit dictated by the container power caps.

Battery Power. Our prototype’s battery bank included multiple 12V, 20Ah deep discharge lithium-ion batteries with a total of 1440Wh capacity. We configured our battery charge controller to only discharge them to 70% depth, such that we classify a 30% state-of-charge as “empty,” since deep discharges significantly reduce a battery’s cycle life. Our battery can support operating the cluster at maximum power for one hour. We set the maximum charging rate for the battery bank to 0.25C, which corresponds to 30 amps (A) at 12V, such that the battery charges to full capacity in 4 hours. We set the maximum discharge rate to 1C, or the rate required to fully discharge the battery in 1 hour. This rate corresponds to 1440W, which is well above the cluster’s maximum power.

The battery above connects to two smart charge controllers, which expose software APIs: one connected to the grid and the other to solar. Our ecovisor can use the grid-connected charge controller to set the battery's charging rate. The solar-connected charge controller automatically uses any excess solar power to charge the battery. Since our prototype does not net meter solar power, we set the charge controller to curtail any excess solar power once the physical battery is fully charged.

Solar Power. Our prototype uses a Solar Array Emulator (SAE) instead of a real solar array to enable repeatable experiments. Our SAE is capable of replaying solar radiation traces, and acts like a programmable power supply that mimics the electrical response of a solar module’s IV curve. Thus, we can replace our SAE with a real solar array without requiring any changes. As mentioned above, we use the Chroma 62020H-150S as our SAE, which is widely used for testing solar modules in industry.

5 OPTIMIZING CARBON-EFFICIENCY

The purpose of our evaluation is to highlight the rich policy space defined by our ecovisor’s narrow API and show that optimizing carbon-efficiency on a shared infrastructure requires application-specific policies. Specifically, we show how our ecovisor can enable a range of different applications to better optimize their carbon-efficiency using an application-specific policy compared to a general one-size-fits-all system policy. Importantly, these applications can operate concurrently on the same infrastructure. In some cases, we re-implement and improve upon applications from prior work implemented on dedicated platforms [70]. Of course, our evaluation does not cover all possible uses of an ecovisor, as there are many potential carbon-efficiency optimizations and abstractions for different types of applications that have yet to be developed. A key goal of ecovisor is to enable the development of new optimizations and abstractions, while supporting existing policies.

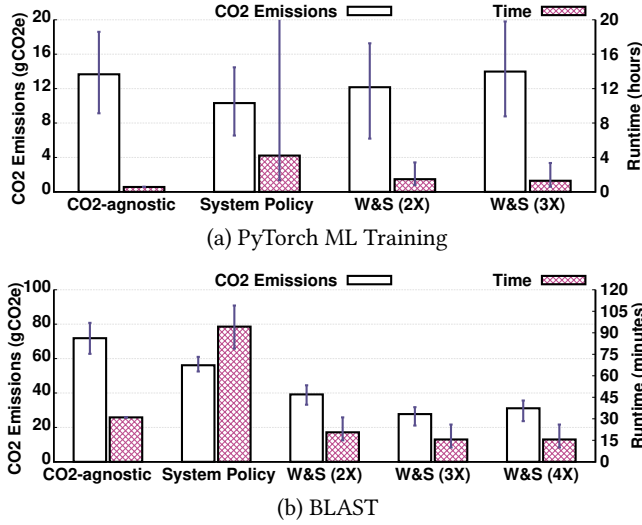


Figure 4: Carbon emissions and runtime for distributed ML training and a high performance computing application using different carbon reduction policies.

5.1 Reducing Carbon

A simple approach to optimizing carbon-efficiency is to suspend execution when grid power’s carbon-intensity increases beyond some threshold and resume it later when carbon-intensity falls below this threshold. Recent work, called WaitAWhile, quantifies the tradeoff between carbon emissions and job completion time using this approach [70]. WaitAWhile’s *suspend-resume* policy is an example of a general system-level policy that applies to all applications on a shared platform. We compare this suspend-resume policy to a new Wait&Scale (W&S) policy we developed, which suspends execution above a threshold and opportunistically scales up resources and energy when carbon emissions are below the threshold. Wait&Scale is an application-specific policy, as different applications have different optimal scale-up factors, which the system may not know. Thus, applications are better positioned to configure their scale-up factor based on their specific scaling properties.

5.1.1 Applications. Our first experiment runs two applications on a shared multi-tenant infrastructure that have different scaling behaviors, which is characterized by each application’s speedup as its number of workers increases.

Our first application is PyTorch, a machine learning framework that we use to train a Resnet34 model [46] on the CIFAR100 dataset [47] for five epochs. The model training job runs on grid power with a variable carbon footprint, which we simulate using data from the carbon emissions of the California Independent System Operation (CAISO) [7] in 2020. Since carbon emissions vary, we ran the experiment ten times and randomly selected the job arrival each time. We set the carbon threshold based on the 30th percentile of carbon-intensity over a 48 hour window in each run.

In this case, our system-level suspend-resume and carbon-agnostic policies run the job on 4 cores, while we run Wait&Scale with scale factors of 2× and 3×, which scale up the job to 8 and 12 cores, respectively, when below the carbon threshold.

The second application is NCBI-BLAST (Basic Local Alignment Search Tool), which is a popular parallel application that searches

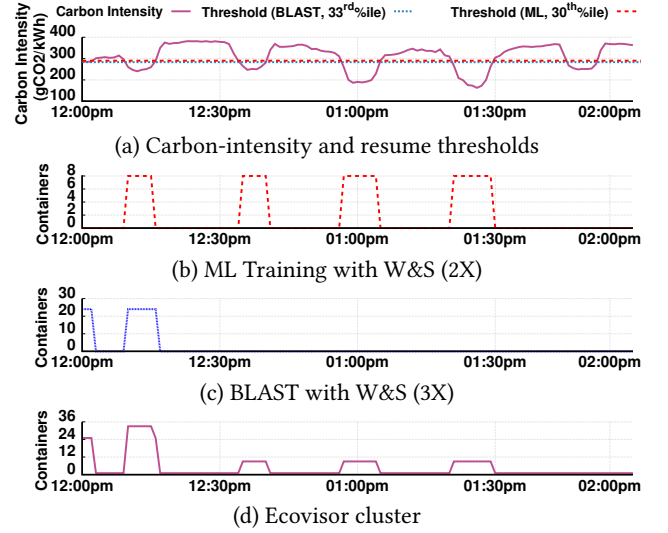


Figure 5: Multi-tenancy of application-specific carbon reduction policies that use the system resources differently based on their scaling properties.

for similarities in nucleotide or protein sequences [6]. We use an elastic version of BLAST-470, which can horizontally scale the number of containers it uses at runtime [41]. Our system-level and carbon-agnostic policies run the BLAST job on 8 cores, while we run Wait&Scale with scale factors of 2×, 3×, and 4×, on 16, 24, and 32 cores, respectively. We set the carbon threshold based on the 33rd percentile of carbon-intensity over the trace duration.

5.1.2 Comparing Carbon Reduction Policies. Figure 4 shows the completion times and carbon emissions under different policies for the two applications, where the error bars depict the standard deviation across the ten experiments. In both cases, the carbon-agnostic policy has the lowest completion time at the cost of higher carbon emissions. The system-level suspend-resume policy reduces carbon emissions by 24.5% and 25.01%, but frequent suspensions increase the running time by 7.4× and 5.1× for the ML training (top) and BLAST (bottom) applications, respectively. The system-level policy also exhibits a highly volatile job runtime, since jobs that happen to start executing during a long high-carbon period are forced to stop and wait until the carbon-intensity decreases.

Wait&Scale overcomes the high completion times of suspend-resume by opportunistically scaling up resources when carbon is low. For the ML training application (top), Wait&Scale (2×) achieves a comparable carbon reduction to suspend-resume, but with a lower runtime penalty (of 2.58×). However, further scale up does not provide additional carbon benefits—Wait&Scale (3×) increases carbon emissions by 14.94% (similar to the system-level policy) while reducing the runtime by only 12.3%. In this case, scaling up requires more coordination among nodes, which causes synchronization delays that limit speed-up and decrease energy-efficiency.

Unlike Resnet training, BLAST is embarrassingly parallel, and thus scales up much more efficiently when carbon-intensity decreases. Wait&Scale (2×) achieves a carbon reduction of 30.1%, while also reducing runtime by 78.15% compared to the system-level policy. Scaling up even further is also beneficial as Wait&Scale

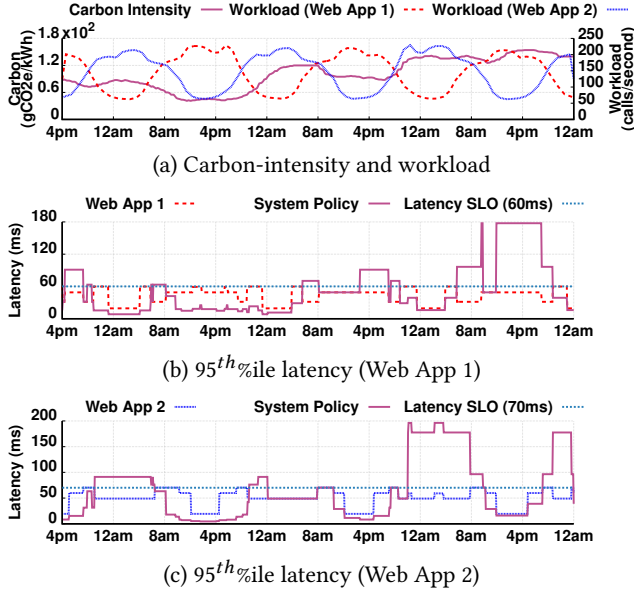


Figure 6: Comparing a static system-level carbon rate-limiting policy with two application-specific dynamic carbon budgeting policies for a distributed web application ((b) and (c)) under varying workloads and carbon-intensity (a).

(3 $\times$) decreases the carbon emissions by 50.05% compared to system-level policy, while further reducing runtime by 83.4%. The benefits of scaling eventually diminish at 4 $\times$ where carbon emissions start increasing, but the job runtime remains the same. For BLAST-470, this happens because BLAST’s central queue server becomes a bottleneck when serving tasks to more than 3 $\times$ workers.

Importantly, our experiments show that our application-specific Wait&Scale policy outperforms the system-level suspend-resume policy. In this case, our ML training job and BLAST exhibit different synchronization overheads, which necessitates using different scale-up factors for optimizing carbon-efficiency.

Key Takeaway. *An ecovisor enables applications to optimally configure their scale-up factor to better optimize carbon-efficiency compared to a system-level suspend-resume policy, which is application-agnostic.*

5.1.3 Multi-tenancy. Our experiment above concurrently ran the ML training job and BLAST on a shared multi-tenant infrastructure using the same physical energy system. Figure 5 shows the per-application and system-wide power usage for both applications at their optimal scale factor. Each application uses different resources and power based on their scaling behavior to individually optimize their carbon-efficiency. Note that the system-wide power also shows a small amount baseline power required to run the ecovisor.

Budgeting Carbon

A disadvantage of the suspend-resume-style carbon reduction policies above is that applications cannot make any forward progress during high carbon periods. Furthermore, the goal of reducing carbon emissions may not be suitable for all the applications, which may instead have a specific carbon emissions budget to operate within. For such scenarios, we next consider an application-agnostic system-level policy that enforces a static carbon budget for each

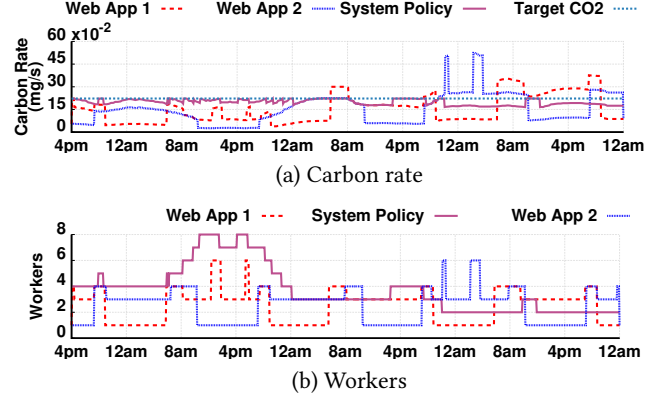


Figure 7: Multi-tenancy of application-specific dynamic carbon budgeting policies that use their system and energy resources differently based on their workload.

application by rate-limiting (or carbon-capping) it at all times. We compare this policy to application-specific policies that enforce a more flexible carbon budget over longer time windows, rather than at all times, which allows applications to breach the cap for short periods, if necessary. We show that such dynamic budgeting policies can provide better performance during periods when both the carbon-intensity and workload intensity are high.

5.2.1 Applications. To illustrate the benefits of application-specific dynamic carbon budgeting, we deploy two multi-tenant distributed web applications using our ecovisor prototype. Both applications include a front-end load balancer that distributes web requests across a cluster, and serves a copy of Wikipedia. The applications use horizontal scaling to regulate power by adding and removing containers from the load balancer’s active set. We subject the applications to two different variable workload demand patterns based on a real-world trace covering 48 hours, and record the latency to satisfy requests [67]. We first run the applications using a static carbon rate limit of 20 mg-CO₂ per second, and then under a dynamic carbon budget equivalent to the product of the same rate and the trace’s length. Our dynamic carbon budgeting policy horizontally scales containers up and down to enforce an SLO on the 95th% latency of 60ms and 70ms for the first and second application, respectively.

5.2.2 Comparing Carbon Budgeting Policies. Figure 6(a) shows the variations over time for the carbon-intensity and workload patterns, which are not aligned. That is, there are periods of both high carbon and workload intensity. Figure 6(b) and (c) then shows the 95th% response time latency for the two web applications over time. As shown in both (b) and (c), the system-level policy violates the latency SLO near the end of the trace during a period of both high carbon and workload intensity, since it does not have the flexibility to increase its container capacity beyond the static carbon cap to handle the more intense workload. In contrast, the dynamic budgeting policy always satisfies the latency SLO over the entire trace by using fewer resources (and less carbon) during periods of low workload and carbon-intensity. The policy then uses its accumulated “carbon credits” to temporarily exceed the carbon cap to serve more intense demand during high carbon-intensity periods, while enforcing the overall carbon budget over a longer period.

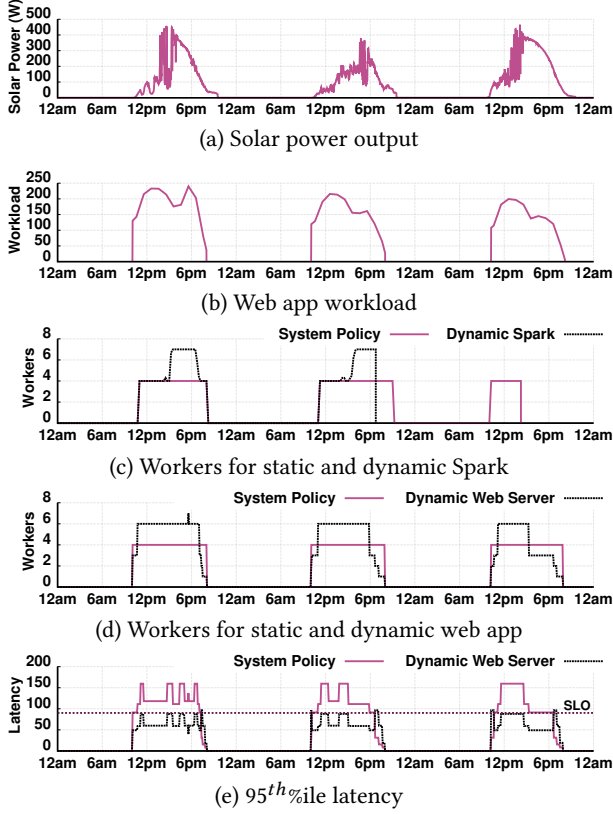


Figure 8: Cluster-level solar power (a) equally divided between Spark and a web application, and workload for web application (b). Number of workers with static system and Spark-specific dynamic battery usage policies (c). Number of workers (d) and 95thile latency (e) with static system and web application-specific dynamic battery usage policies.

Note that the system-level rate-limiting policy occasionally provides much lower latency than the SLO (by over-provisioning when carbon is low), while the dynamic carbon budgeting policy uses fewer resources when they are not needed and leverages the carbon savings to satisfy load spikes. Overall, the dynamic carbon budgeting policy has 22.8% and 23.4% lower carbon emissions for both applications compared to the system-level policy, since it operates well below the target carbon rate most of the time. This also demonstrates that the application-specific policy enables the applications to dynamically manage their emissions in different ways, while satisfying the overall carbon budget, which is not possible using the static system-level rate-limiting policy.

Key Takeaway. Applications are much better positioned to manage a specified carbon budget to meet their performance requirements compared to a static system-level rate-limiting policy.

5.2.3 Multi-tenancy. Finally, Figures 7(a) and 7(b) show the carbon rate and the number of containers for the two applications over time. Both applications, when using dynamic carbon budgeting policy, consume fewer resources and energy when carbon emissions are low, i.e., only enough to satisfy their SLO, while the static system-level rate-limiting policy uses as many resources and energy as

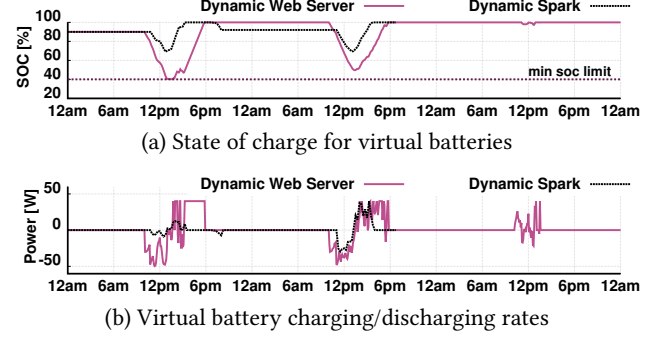


Figure 9: Multi-tenancy of application-specific virtual battery usage policies, where each application uses their virtual battery differently based on their requirements.

necessary to satisfy its target carbon rate. Although the applications run on the same cluster at the same time, their carbon emissions and container capacity differ depending on their workload.

5.3 Leveraging Virtual Batteries

The applications above optimize carbon-efficiency using grid power. We next examine applications that implement zero-carbon policies using solar power and batteries. Although solar power has zero carbon-intensity, its output is volatile due to changing environmental conditions. As we show, our ecovisor’s virtual batteries can supply applications a minimum guaranteed amount of power when solar output falls below a threshold, smoothing out the volatility.

5.3.1 Applications. To illustrate our zero-carbon policies, we deploy two applications that share a solar panel and physical battery. Our first application is a “delay-tolerant” distributed Spark job running on our ecovisor prototype powered by intermittent solar and a battery. In this case, the job is an image preprocessing and feature extraction task written using pyspark running on Spark 3.2.0. Spark runs on solar power and a battery during the day, with the battery ensuring a minimum guaranteed power. Although grid power is available at night, to maintain a zero carbon footprint, we checkpoint completed operations to the Hadoop Distributed File System (HDFS), and wait until the next morning to resume Spark computations. Incomplete workers are terminated without checkpointing every evening and their in-memory results are lost.

Our second application is a web-based monitoring and logging application, which monitors and logs the power generation of our ecovisor’s physical and virtual solar arrays. This application is similar to publicly-deployed services for monitoring renewable-powered computing infrastructure [26, 28]. Each web request logs the current power generation in the web application. Since there is no solar generation at night, the application sees only a daytime workload and is dormant during nighttime hours when there is no data to log. Like Spark, the web application runs on solar power and batteries during the day and stays suspended during the night. We set a target latency SLO of 100ms for web request processing.

5.3.2 Comparing Battery Usage Policies. Our system-level policy for both applications is to use the battery to smooth out the variations in solar power and provide a minimum guaranteed power. Figure 8(a) shows that the total solar power is equally divided between

the two applications. Figure 8(c) shows the number of workers for a static (system-level) and Spark-specific dynamic policies. The system-level policy is conservative and avoids losing computation by using a fixed number of workers that are always available. In contrast, the Spark-specific dynamic policy opportunistically scales up the number of workers to leverage excess solar when the battery is fully charged. While any work performed by the additional workers might be lost if they are terminated before checkpointing the work, they mostly perform useful computation, which reduces the application runtime by 39%.

Figure 8(b) shows the workload trace for the web application, which varies over time as the number of applications running and monitoring/logging their resources come and go. Figure 8(d) shows the number of workers for a static (system-level) and application-specific dynamic policies. Since the static (system-level) policy only has fixed power available, it runs only 4 workers irrespective of the workload. In contrast, the dynamic policy can scale up to a higher number of workers to process a higher request rate. Figure 8(c) shows the 95thile latency for the web application. The static (system-level) policy safeguards against the server going down, resulting in a much higher latency under high workload, while the dynamic policy always able meets the target latency SLO. **Key Takeaway.** *Our ecovisor enables applications to exercise control over their virtual batteries to satisfy their application-specific performance requirements, such as a low runtime versus a low latency, compared to an application-agnostic system-level policy.*

5.3.3 Multi-tenancy. Figure 9(a) and 9(b) show the state-of-charge and actual charging and discharging patterns, respectively, for the virtual batteries allocated to each application. Both applications concurrently ran on a shared multi-tenant platform, but their battery usage patterns differ significantly depending on their requirements.

5.4 Directly Exploiting Solar Power Efficiency

Some parallel applications may more directly exploit solar power without using any battery capacity, despite its volatility, using vertical scaling. Since our ecovisor enables applications to balance power’s supply and demand, these applications can explicitly allocate their limited solar power across a set of containers such that the sum of containers’ power caps does not exceed the supply of solar power. In this case, applications should allocate their limited solar power to where it can be used most productively. Since servers are not energy-proportional, they consume some power even when idle. Thus, servers’ most energy-efficient operating point is at 100% of their allocated energy, and any idleness due to operating below this point wastes energy. However, parallel applications often have tasks that are idle due to performing I/O, such as due to periodic task synchronization in the PyTorch training above. Such parallel applications frequently exhibit straggler tasks that increase running time by forcing other tasks to wait [23, 24, 39]. Importantly, executing parallel applications on a limited amount of solar power can exacerbate the performance issues above.

5.4.1 Applications. To illustrate our policies for directly exploiting solar power, we deploy two configurations of a synthetic parallel job. In the first configuration, the job periodically synchronizes across tasks and performs I/O, and uses vertical scaling on all containers

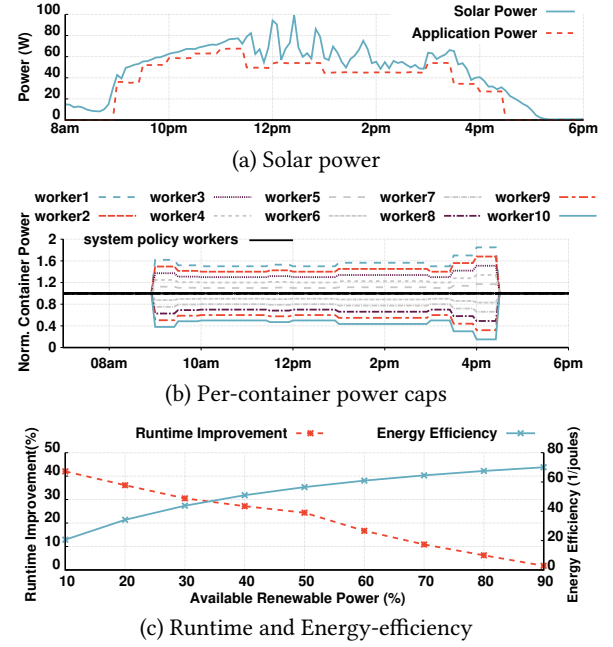


Figure 10: Comparison of a static system-level and dynamic application-specific policy for setting per-container power caps (b) for a parallel job running across 10 nodes using the solar energy in (a). The dynamic policy has a better runtime and energy-efficiency (c).

to match the available solar power. In the second, we configure the parallel job to perform straggler mitigation by tracking the progress of each task, and issuing a new replica for any slow task. For this configuration, we randomly inject straggler tasks into the workload. We implement two power capping policies for the first configuration: (i) a system-level policy that sets static caps across 10 nodes, and (ii) an application-specific policy that dynamically varies caps to ensure each node uses all of its allocated energy, i.e., 100% resource utilization. Finally, the third policy handles stragglers by allocating extra resources when excess energy is available.

5.4.2 Comparing Solar Policies. Figure 10(a) shows solar power availability for a single day. In Figure 10(b), the dynamic power caps differ across the 10 nodes relative to the static cap (center line) over the trace. Figure 10(c) then scales the solar output from (a) by the percentage on the x-axis and plots the runtime improvement from using the dynamic policy (left y-axis) and its energy-efficiency (right y-axis). The graph shows that as solar energy decreases, the importance of dynamically balancing power to reduce runtime increases. Energy-efficiency increases as available solar power increases, since each node’s base power is amortized over more productive work, which again illustrates the inefficiency of solar power.

Finally, Figure 11 shows the the third policy as we scale the solar output from Figure 10(a) up, which results in an excess of solar energy. If applications cannot store the excess energy, they are incentivized to use it immediately, even if that usage is not entirely efficient. Figure 11 shows that as solar energy increases, our application’s overall energy-efficiency decreases, since we consume that energy by spawning more task replicas. However, in this case, the absolute decrease in energy-efficiency is not important, since the

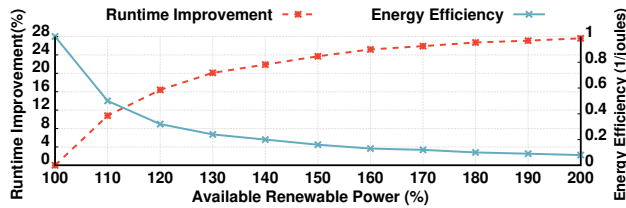


Figure 11: Mitigating stragglers using replica tasks is one way to productively consume excess renewable energy.

excess solar energy would have otherwise been wasted. In this case, the application decreases its runtime by using the excess energy for straggler mitigation, although it sees diminishing returns as it submits more replicas (since at most one replica task will finish).

Key Takeaway. *Our ecovisor enables dynamic application-specific policies that improve solar efficiency and performance using vertical scaling and straggler mitigation techniques compared to a static system-level policy.*

6 RELATED WORK

Our work builds on prior work in managing energy, including integrating renewables and batteries into datacenters, and more recent work on managing carbon emissions.

Energy Management. There has been significant work on improving energy-efficiency and managing energy in computer systems over the past three decades. This work has been highly successful in improving computing’s energy-efficiency and reducing energy costs. Our work differs in its focus on carbon-efficiency, which is different from energy-efficiency. Designing energy-efficient systems requires looking “inward” at various components to optimize their energy use, while designing carbon-efficient systems instead requires looking “outward” to the local energy system and grid to understand energy’s source and characteristics.

Our work is also related to prior work that virtualizes power [29, 53, 63, 69] and exposes power management to applications [29, 49, 69] across a variety of platforms. For example, Nathuji and Schwan integrate hardware power management mechanisms with hypervisors to enable VM-level power management for servers [53]. Similarly, Shen et al. propose power containers to enable fine-grained power management on a per-container basis. Our work leverages similar techniques for attributing and capping power for specific containers based on their resource usage [48, 60]. However, our work differs in its focus on using these mechanisms to expose visibility and control of the energy system, including power’s carbon and availability characteristics, as well as control of a virtual battery. This visibility and control enables applications to adapt their behavior to optimize carbon-efficiency in addition to energy-efficiency.

Finally, prior work on energy management has also proposed exposing power management to applications across a variety of platforms, including cloud platforms [29, 69], individual servers, and mobile devices [49]. Our work differs in that reducing power usage is not the same as reducing carbon emissions.

Renewables and Storage Integration. There has also been significant prior work on integrating renewables and energy storage into datacenters and optimizing applications for them. Researchers have long recognized the potential to adapt cloud applications to variable renewable energy by adjusting their resource usage or migrating

jobs [21]. Thus, prior work has optimized numerous applications with a wide range of characteristics and performance requirements, including Hadoop [35], job schedulers [33], key-value stores [45], distributed storage [62], and load balancers [38], to run on variable renewable energy. While this prior work must implicitly embed ecovisor-like APIs that interact with the physical energy system within their system software, they do not define and expose these APIs externally, and thus cannot support different application-level carbon and energy management policies. Importantly, our ecovisor is capable of concurrently running all of the applications above (and others) on a shared infrastructure. GreenSwitch is perhaps most related to our ecovisor approach, as it defines a model-based policy for dynamically scheduling workload and selecting energy sources, e.g., grid, battery, solar, to optimize various objectives, e.g., cost, peak power, and carbon [34]. However, as above, GreenSwitch implements its policy at the system-level and does not expose visibility or control of the energy system to applications.

There has also been significant prior work on leveraging batteries in cloud datacenters to reduce energy costs and provide power during outages [36, 55, 68]. Our work provides applications the visibility and control necessary to actually implement these optimizations on a shared multi-tenant infrastructure, which prior work has not previously addressed, and also provides a platform for developing new optimizations, as we show in §5.

Carbon Management. Recent work has recognized the importance of reducing carbon emissions, and has attempted to quantify the carbon emissions of running particular applications on cloud platforms [25, 29, 57, 66]. In addition, recent work has also attempted to quantify the carbon footprint of cloud datacenters, including the carbon emissions embedded in hardware, i.e., Scope 3 emissions [54]. While quantifying the scope of the problem for particular applications and platforms is certainly useful, this prior work does not provide any actionable solutions for reducing carbon emissions or enabling carbon-efficiency optimizations. As we show, carbon-efficiency optimizations are now possible with the emergence of carbon information services, such as electricityMap [9], which provide real-time estimates of grid power’s carbon-intensity. Finally, recent work has also proposed nascent carbon-efficiency optimizations, such as WaitAWhile [70]. A key goal of our ecovisor is to enable these and other application-specific carbon-efficiency optimizations concurrently on a shared platform.

7 CONCLUSION

Enabling the design of carbon-efficient applications is an increasingly important research area that is necessary to halt climate change. To enable the design of carbon-efficient applications, we propose an ecovisor that virtualizes the physical energy system and exposes software-defined visibility into, and control of, it to applications. Our approach pushes visibility and control of the energy system from hardware into software, enabling applications to optimize carbon-efficiency based on their own application-specific requirements by responding to variations in grid power’s carbon-intensity and renewable power’s availability. We build a small-scale ecovisor prototype, and demonstrate its ability to support a variety of carbon-efficiency optimizations for different applications. In the future, we plan to enable coordination between distributed ecovisor clusters to enable geo-distributed applications.

ACKNOWLEDGEMENTS

We thank the ASPLOS reviewers for their valuable comments, which improved the quality of this paper, and electricityMap for access to their carbon-intensity data. This research is supported by NSF grants 2213636, 2105494, 2021693, 2020888, as well as VMware.

REFERENCES

- [1] Reuters, Amazon Vows to be Carbon Neutral by 2040, buying 100,000 Electric Vans. <https://www.reuters.com/article/us-amazon-environment/amazon-vows-to-be-carbon-neutral-by-2040-buying-100000-electric-vans-idUSKBN1W41ZV>, September 19th 2019.
- [2] Amazon EC2 Spot Instances. <https://aws.amazon.com/ec2/spot/>, Accessed March 2022.
- [3] Aws autoscaling. <https://aws.amazon.com/autoscaling/>, Accessed February 2022.
- [4] Azure Monitor. <https://azure.microsoft.com/en-us/services/monitor/>, Accessed July 2022.
- [5] Azure Spot Virtual Machines. <https://azure.microsoft.com/en-us/pricing/spot/>, Accessed March 2022.
- [6] Basic Local Alignment Search Tool. <https://blast.ncbi.nlm.nih.gov/Blast.cgi>, Accessed March 2022.
- [7] California ISO. <https://www.aiso.com/Pages/default.aspx>, Accessed March 2022.
- [8] Carbon Free Energy for Google Cloud Regions. <https://cloud.google.com/sustainability/region-carbon>, Accessed March 2022.
- [9] Electricity Map. <https://www.electricitymap.org/map>, Accessed March 2022.
- [10] Google cloud carbon footprint: Measure, report and reduce your cloud carbon emissions. <https://cloud.google.com/carbon-footprint>, Accessed July 2022.
- [11] Google Data Centers Efficiency. google.com/about/datacenters/efficiency/, Accessed March 2022.
- [12] Greenhouse Gas Protocol. <https://ghgprotocol.org/>, Accessed March 2022.
- [13] IPMI Overview. <https://www.ibm.com/docs/en/power9/0009-ESS?topic=ipmi-overview>, Accessed March 2022.
- [14] Overview of autoscale in microsoft azure. <https://docs.microsoft.com/en-us/azure/azure-monitor/autoscale/autoscale-overview>, Accessed February 2022.
- [15] Python Tesla Powerwall API. <https://pypi.org/project/tesla-powerwall/>, Accessed March 2022.
- [16] ROCK64. <https://www.pine64.org/devices/single-board-computers/rock64/>, Accessed March 2022.
- [17] Tesla Powerwall Modes of Operation with Solar. https://www.tesla.com/en_au/support/energy/powerwall/mobile-app/modes-of-operationwithsolar, Accessed March 2022.
- [18] Uptime Institute Global Data Center Survey 2021: Growth Stretches an Evolving Sector. <https://uptimeinstitute.com/resources/asset/2021-data-center-industry-survey>, Accessed May 2022.
- [19] WattTime. <https://www.watttime.org/>, Accessed March 2022.
- [20] Nicola Acutt. Radius: Stories at the Edge, Achieving Carbon Neutrality. <https://www.vmware.com/radius/achieving-carbon-neutrality/>, November 1st 2018.
- [21] Anup Agarwal, Jinghan Sun, Shadi Noghabi, Srinivasan Iyengar, Anirudh Badam, Ranveer Chandra, Srinivasan Seshan, and Shivkumar Kalyanaram. Redesigning Cloud Computing for Renewable Energy. In *Proceedings of the Twentieth ACM Workshop on Hot Topics in Networks (HotNets)*, November 2021.
- [22] Dario Amodei, Danny Hernandez, Girish Sastry, Jack Clark, Greg Brockman, and Ilya Sutskever. AI and Compute. <https://openai.com/blog/ai-and-compute/>, May 16th 2018.
- [23] Ganesh Ananthanarayanan, Ali Ghodsi, Scott Shenker, and Ion Stoica. Effective Straggler Mitigation: Attack of the Clones. In *USENIX Symposium on Networked System Design and Implementation (NSDI)*, April 2013.
- [24] Ganesh Ananthanarayanan, Michael Chien-Chun Hung, Xiaoqi Ren, Ion Stoica, Adam Wierman, and Minlan Yu. GRASS: Trimming Stragglers in Approximation Analytics. In *USENIX Symposium on Networked System Design and Implementation (NSDI)*, April 2014.
- [25] Emily M Bender, Timnit Gebru, Angelina McMillan-Major, and Shmargaret Shmitchell. On the Dangers of Stochastic Parrots: Can Language Models Be Too Big? In *Proceedings of the 2021 ACM Conference on Fairness, Accountability, and Transparency (FAcT)*, March 2021.
- [26] T. Brain, A. Nathanson, and B. Piantella. Solar Protocol. <http://solarprotocol.net/>, July 26th 2022.
- [27] Maxime Colmant, Pascal Felber, Romain Rouvoy, and Lionel Seinturier. WattsKit: Software-Defined Power Monitoring of Distributed Systems. In *17th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGRID)*, April 2017.
- [28] K. De Decker. This Website Runs on a Solar Powered Server Located in Barcelona. <https://solar.lowtechmagazine.com/power.html>, July 26th 2022.
- [29] Nan Deng, Christopher Stewart, Daniel Gmach, and Martin Arlitt. Policy and Mechanism for Carbon-Aware Cloud Applications. In *2012 IEEE Network Operations and Management Symposium*, 2012.
- [30] Dawson R. Engler, M. Frans Kaashoek, and James O'Toole. Exokernel: An Operating System Architecture for Application-Level Resource Management. In *ACM Symposium on Operating System Principles (SOSP)*, 1995.
- [31] Darrell Etherington. TechCrunch, Google Claims Net Zero Carbon Footprint over its Entire Lifetime, Aims to only use Carbon-Free Energy by 2030. <https://techcrunch.com/2020/09/14/google-claims-net-zero-carbon-footprint-over-its-entire-lifetime-aims-to-only-use-carbon-free-energy-by-2030/>, September 14th 2020.
- [32] Ali Ghodsi, Matei Zaharia, Benjamin Hindman, Andy Konwinski, Scott Shenker, and Ion Stoica. Dominant Resource Fairness: Fair Allocation of Multiple Resource Types. In *USENIX Symposium on Networked System Design and Implementation (NSDI)*, April 2011.
- [33] Inigo Goiri, Ryan Beauchea, Kien Le, Thu D. Nguyen, Md. E. Haque, Jordi Guitart, Jordi Torres, and Ricardo Bianchini. GreenSlot: Scheduling Energy Consumption in Green Datacenters. In *ACM/IEEE International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, November 2011.
- [34] Inigo Goiri, William Katsak, Kien Le, Thu D. Nguyen, and Ricardo Bianchini. Parasol and GreenSwitch: Managing Datacenters Powered by Renewable Energy. In *ACM Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, March 2013.
- [35] Inigo Goiri, Kien Le, Thu D. Nguyen, Jordi Guitart, Jordi Torres, and Ricardo Bianchini. GreenHadoop: Leveraging Green Energy in Data-processing Frameworks. In *ACM European Conference on Computer Systems (EuroSys)*, April 2012.
- [36] Sriram Govindan, Anand Sivasubramanian, and Bhuvan Urganonkar. Benefits and Limitations of Tapping into Stored Energy for Datacenters. In *Proceedings of the 38th Annual International Symposium on Computer Architecture (ISCA)*, June 2011.
- [37] Developer Guide. Amazon Cloudwatch. 2009.
- [38] Vani Gupta, Prashant Shenoy, and Ramesh K Sitaraman. Combining Renewable Solar and Open Air Cooling for Greening Internet-Scale Distributed Networks. In *Proceedings of the Tenth ACM International Conference on Future Energy Systems (e-Energy)*, June 2019.
- [39] Aaron Harlap, Henggang Cui, Wei Dai, Jinliang Wei, Gregory Ganger, Phillip Gibbons, Garth Gibson, and Eric Xing. Addressing the Straggler Problem for Iterative Convergent Parallel ML. In *Symposium on Cloud Computing (SoCC)*, September 2016.
- [40] Fiona Harvey. The Guardian, Major Climate Changes Inevitable and Irreversible – IPCC's Starkest Warning Yet. <https://www.theguardian.com/science/2021/aug/09/humans-have-caused-unprecedented-and-irreversible-change-to-climate-scientists-warn>, August 9th 2021.
- [41] Valerie Hendrix, James Fox, Devarshi Ghoshal, and Lavanya Ramakrishnan. Tigris Workflow Library: Supporting Scientific Pipelines on HPC Systems. In *16th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGRID)*, May 2016.
- [42] Benjamin Hindman, Andy Konwinski, Matei Zaharia, Ali Ghodsi, Anthony Joseph, Randy Katz, Scott Shenker, and Ion Stoica. Mesos: A Platform for Fine-grained Resource Sharing in the Data Center. In *USENIX Symposium on Networked Systems Design and Implementation (NSDI)*, March 2011.
- [43] Umair Irfan. Vox, Can You Really Negate Your Carbon Emissions? Carbon Offsets, Explained. <https://www.vox.com/2020/2/27/20994118/carbon-offset-climate-change-net-zero-neutral-emissions>, February 27th 2020.
- [44] Penny Jones. DataCenterDynamics, Apple Confirms Solar Farm at Maiden Data Center. <https://www.datacenterdynamics.com/en/news/apple-confirms-solar-farm-at-maiden-data-center/>, February 21st 2012.
- [45] William Katsak, Inigo Goiri, Ricardo Bianchini, and Thu Nguyen. GreenCassandra: Using Renewable Energy in Distributed Structured Storage Systems. In *International Conference on Green and Sustainable Computing (IGSC)*, June 2015.
- [46] Brett Koonce. Resnet 34. In *Convolutional Neural Networks with Swift for TensorFlow*. Springer, 2021.
- [47] Alex Krizhevsky, Geoffrey Hinton, et al. Learning Multiple Layers of Features from Tiny Images. 2009.
- [48] Shaohong Li, Xi Wang, Faria Kalim, Xiao Zhang, Sangeetha Abdu Jyothi, Karan Grover, Vasileios Kontorinis, Nina Narodytska, Owolabi Legunsen, Sreekumar Kodakara, et al. Thunderbolt: Throughput-Optimized, Quality-of-Service-Aware Power Capping at Scale. In *USENIX Symposium on Operating System Design and Implementation (OSDI)*, November 2020.
- [49] Xiaotao Liu, Prashant Shenoy, and Mark D Corner. Chameleon: Application-level Power Management. *IEEE Transactions on Mobile Computing*, 2008.
- [50] Canonical Ltd. LXD. <https://linuxcontainers.org/lxd/introduction/>.
- [51] Eric Masanet, Arman Shehabi, Nuoa Lei, Sarah Smith, and Jonathan Koomey. Recalibrating Global Data Center Energy-use Estimates. *Science*, 367(6481):984–986, February 2020.
- [52] Valérie Masson-Delmotte, Panmao Zhai, Anna Pirani, Sarah L Connors, Clotilde Péan, Sophie Berger, Nada Caud, Yang Chen, Leah Goldfarb, Melissa I Gomis, et al. Summary for Policymakers. in: *Climate Change 2021: The Physical Science*

- Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Technical report, United Nations Intergovernmental Panel on Climate Change (IPCC), 2021.
- [53] Ripal Nathuji and Karsten Schwan. VirtualPower: Coordinated Power Management in Virtualized Enterprise Systems. In *ACM Symposium on Operating System Principles (SOSP)*, October 2007.
 - [54] Kevin O'Sullivan. The Irish Times, Facebook Commits to Net-Zero Carbon Emissions by 2030. <https://www.irishtimes.com/news/environment/facebook-commits-to-net-zero-carbon-emissions-by-2030-1.4354701>, September 15th 2020.
 - [55] Darshan S. Palasamudram, Ramesh K. Sitaraman, Bhuvan Urgaonkar, and Rahul Urgaonkar. Using Batteries to Reduce Power Costs of Internet-Scale Distributed Networks. In *ACM Symposium on Cloud Computing (SoCC)*, October 2012.
 - [56] Andy Patrizio. Data Center Dynamics, The Quest to Run Data Centers on Battery Power. <https://www.datacenterdynamics.com/en/analysis/the-quest-to-run-data-centers-on-battery-power/>, April 5th 2021.
 - [57] David Patterson, Joseph Gonzalez, Quoc Le, Chen Liang, Lluis-Miquel Munguia, Daniel Rothchild, David So, Maud Texier, and Jeff Dean. Carbon Emissions and Large Neural Network Training. Technical report, arXiv, April 2021.
 - [58] Sundar Pichai. Google Blog, New progress toward our 24/7 carbon-free energy goal. <https://blog.google/outreach-initiatives/sustainability/new-progress-toward-our-247-carbon-free-energy-goal>, April 20th 2021.
 - [59] John Roach. Microsoft datacenter batteries to support growth of renewables on the power grid. <https://news.microsoft.com/innovation-stories/ireland-wind-farm-datacenter-ups/>, July 7th 2022.
 - [60] Varun Sakalkar, Vasileios Kontorinis, David Landhuis, Shaohong Li, Darren De Ronde, Thomas Blooming, Anand Ramesh, James Kennedy, Christopher Malone, Jimmy Clidas, et al. Data Center Power Oversubscription with a Medium Voltage Power Plane and Priority-Aware Capping. In *ACM Symposium on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, March 2020.
 - [61] Jerome H. Saltzer, David P. Reed, and David D. Clark. End-To-End Arguments in System Design. *ACM Transactions on Computer Systems*, November 1984.
 - [62] Navin Sharma, Sean Barker, David Irwin, and Prashant Shenoy. Blink: Managing Server Clusters on Intermittent Power. In *ACM Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, March 2011.
 - [63] Kai Shen, Arrivindh Shriraman, Sandhya Dwarkadas, Xiao Zhang, and Zhuan Chen. Power Containers: An OS Facility for Fine-grained Power and Energy Management on Multicore Servers. In *ACM Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, March 2013.
 - [64] Rahul Singh, David Irwin, Prashant Shenoy, and K.K. Ramakrishnan. Yank: Enabling Green Data Centers to Pull the Plug. In *USENIX Symposium on Networked Systems Design and Implementation (NSDI)*, April 2013.
 - [65] Brad Smith. Official Microsoft Blog, Microsoft will be Carbon Negative by 2030. <https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/>, January 16th 2020.
 - [66] Emma Strubell, Ananya Ganesh, and Andrew McCallum. Energy and Policy Considerations for Modern Deep Learning Research. In *AAAI Conference on Artificial Intelligence (AAAI)*, February 2020.
 - [67] Guido Urdaneta, Guillaume Pierre, and Maarten van Steen. Wikipedia workload analysis for decentralized hosting. *Elsevier Computer Networks*, July 2009. http://www.globule.org/publi/WWADH_comnet2009.html.
 - [68] Rahul Urgaonkar, Bhuvan Urgaonkar, Michael J Neely, and Anand Sivasubramanian. Optimal Power Cost Management Using Stored Energy in Data Centers. In *Proceedings of the ACM Conference on Measurement and Analysis of Computing Systems (SIGMETRICS)*, March 2011.
 - [69] Cheng Wang, Bhuvan Urgaonkar, George Kesidis, Uday V Shanbhag, and Qian Wang. A Case for Virtualizing the Electric Utility in Cloud Data Centers. In *USENIX Workshop on Hot Topics in Cloud Computing (HotCloud)*, July 2014.
 - [70] Philipp Wiesner, Ilja Behnke, Dominik Scheinert, Kordian Gontarska, and Lauritz Thamsen. Let's Wait Awhile: How Temporal Workload Shifting Can Reduce Carbon Emissions in the Cloud. In *Proceedings of the 22nd International Middleware Conference (Middleware)*, December 2021.