A Holistic Approach for Designing Carbon Aware Datacenters

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Abstract—Technology companies have been leading the way to a renewable energy transformation, by investing in renewable energy sources to reduce the carbon footprint of their datacenters. In addition to helping build new solar and wind farms, companies make power purchase agreements or purchase carbon offsets, rather than relying on renewable energy every hour of the day, every day of the week (24/7). Relying on renewable energy 24/7 is challenging due to the intermittent nature of wind and solar energy. Inherent variations in solar and wind energy production causes excess or lack of supply at different times. To cope with the fluctuations of renewable energy generation, multiple solutions must be applied. These include: capacity sizing with a mix of solar and wind power, energy storage options, and carbon aware workload scheduling. However, depending on the region and datacenter workload characteristics, the carbonoptimal solution varies. Existing work in this space does not give a holistic view of the trade-offs of each solution and often ignore the embodied carbon cost of the solutions.

In this work, we provide a framework, Carbon Explorer, to analyze the multi-dimensional solution space by taking into account operational and embodided footprint of the solutions to help make datacenters operate on renewable energy 24/7. The solutions we analyze include capacity sizing with a mix of solar and wind power, battery storage, and carbon aware workload scheduling, which entails shifting the workloads from times when there is lack of renewable supply to times with abundant supply. Carbon Explorer will be open-sourced soon.

I. Introduction

Information and communications technology (ICT) has transformed many aspects of our lives such as education, entertainment, business, and transportation. Increasing demand for ICT significantly increases demand for electricity. Data centers world-wide are estimated to consume 205 TWh of electricity in 2018 [47], exceeding the annual consumption of countries such as Ireland and Denmark [54]. The energy demand of ICT is projected to account for 7% to 20% of the global demand by 2030 [1], [25]. As ICT continues to grow, we expect hyperscale datacenters to consume more electricity and generate larger environmental footprints.

Technology companies mitigate computing's environmental footprint by operating hyperscale datacenters with carbon free energy [14], [26], [29]. Amazon, Meta, and Google have invested in over 22 GW of renewable energy generation to meet their *Net Zero* commitments for datacenters and other operational activities. These investments in renewable energy for computing align with broader trends in Figure 1. Renewable energy generation is projected to increase to 42% of the

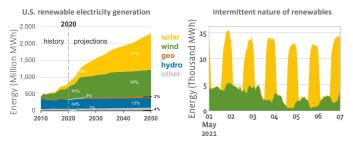


Fig. 1. [left] Historical and projection of growth of renewable energy in the US electricity grid [2010-2050]. [right] Hourly wind and solar energy generation in California grid during a week of time-frame.

total by 2050 as the United States seeks to achieve its *Net Zero* goals [59]. Moreover, 47% and 34% of this renewable energy will come from solar and wind, respectively.

Despite these promising trends, computing with renewable energy twenty-four hours a day, seven days a week — 24/7 operational carbon-free computing — is challenging because renewable energy generation is highly intermittent. The broad deployment of solar and wind farms will lead to increasingly severe hourly and seasonal fluctuations in energy generation. At times, the grid's supply of renewable energy may exceed the demand, forcing inefficient curtailments that deactivate renewable energy generation in order to match supply with demand and reduce congestion on the power transmission network [4], [7], [8], [37]. At other times, solar and wind energy is scarce and datacenters (DCs) risk consuming carbonintensive energy from gas or coal from the grid despite their investments in renewable generation. Under these conditions, datacenters can claim Net Zero operations on an annual basis, matching total renewable energy credits generated by its wind and solar investments against the energy consumed by its computation, yet continue to generate carbon emissions on an hourly basis due to fluctuations in wind and solar supply. Thus, more must be done to eliminate carbon emissions for datacenter computing in every hour of every day.

Various strategies have been explored to help datacenters cope with the intermittent nature of renewable energy. First, demand response strategies can predict renewable energy supply and datacenter energy demand, and schedule computation to align supply and demand [3], [50], [65], [70]. Second, energy storage can reduce datacenter exposure to fluctuations in renewable energy supply [40], [43]. Third, further investment in wind and solar can ensure sufficient supply for more

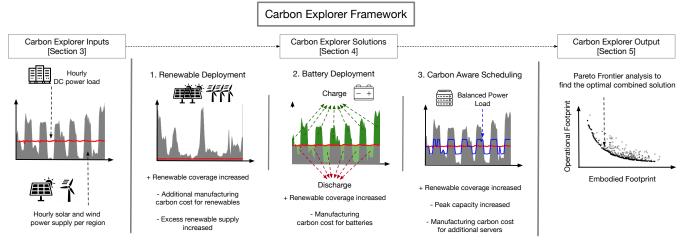


Fig. 2. Design Overview for Carbon Explorer. Carbon Explorer considers important characteristics, such as time-series power demand of large-scale datacenters and renewable energy availability on the power grids, as inputs. Carbon Explorer characterizes the design space across renewable energy investments, energy storage, and computation shifting. Carbon Explorer provides *quantitative measures for strategies to achieve carbon-minimum settings*.

hours and days of the year. These strategies have significant implications for datacenter infrastructure. Datacenters may need additional servers that perform extra computation when carbon-free energy is abundant [71], batteries that provide capacity well beyond that of today's existing power supplies, as well as investments in energy generation that reflect the datacenter's location and the relative availability of wind and solar. All of this infrastructure incurs additional costs.

In this paper, we present a framework for defining and exploring the design space for 24/7 carbon-free computing. The framework consumes a vast amount of data that details energy demands from hyperscale datacenters and energy supplies from renewable sources across locations in the United States. It models the effect of investments in renewable energy generation, in battery capacity, and in server capacity to support computation deferred by demand response scheduling. Finally, the framework performs a Pareto analysis to determine the overall carbon footprint of each design point. Benefits correspond to operational carbon reduction, 24/7 coverage, the percentage of hours that consume carbon-free energy for a year of datacenter computation. Costs correspond to the embodied carbon incurred when manufacturing the required infrastructure. In summary, the main contributions of the paper are:

- We propose a design space exploration framework Carbon Explorer that allows system architects to optimize environmentally-sustainable hyperscale datacenters. Carbon Explorer provides a quantitative measure for the multi-dimensional design space and reveals costeffective infrastructure decisions that permit 24/7 carbon-free computing (Section II).
- We study three important scenarios in which datacenters consume energy directly from the grid, use power purchase agreements, and pursue 24/7 operational carbonfree computing. Based on these, we find that carbonoptimal solutions depend heavily on datacenter workload demand, renewable energy supply, and the efficiency of

energy storage (Section III).

- We take a holistic approach to explore and characterize
 the design space of making a datacenter operate 24/7
 on renewable energy by taking into account embodied
 carbon footprint an important but under-explored area
 of the design space. This embodied carbon footprint can
 come from the added server capacities, energy storage
 units, and renewable energy infrastructures (Section IV).
- Using Carbon Explorer , we demonstrate that carbonoptimal settings vary depending on datacenter locations.
 When there already exists sufficient server capacity held
 in reserve (i.e., Oregon and Utah datacenters), Renewables+Scheduling is the most carbon-efficient strategy to
 reach 24/7. In contrast, for solar-only geographic regions
 (i.e., North Carolina), Renewables+Battery is the only
 viable solution to reach 24/7 (Section V).
- Compared to a *Renewables-Only* strategy, *Renewables+Scheduling* increases 24/7 coverage from 99.4% to 100% in Oregon, from 53.5% to 71% in North Carolina, and from 94.8% to 98% in Utah. *Renewable+Battery* achieves 100% coverage for all three datacenters, but batteries incur additional embodied carbon cost *Renewable+Battery* is not always the carbon-optimal strategy.

Climate change is an existential crisis. We hope Carbon Explorer will enable future works to deploy carbon-optimal technologies and achieve environmentally-sustainable computing in the years to come.

II. CARBON EXPLORER

Carbon Explorer is a design space exploration framework which takes a holistics approach to achieve carbon-optimal strategies. Figure 2 illustrates the overall design of the framework. Carbon Explorer considers two important characteristics as inputs: time-series power demand of large-scale datacenters and the intermittent nature of renewable energy availability on the power grids at specific geographic locations (Figure 2-left). Next, Carbon Explorer characterizes the solution space across the following dimensions (Figure 2-center):

- Investments on various renewable energy types,
- The amount of energy storage, and
- Computation shifting.

Finally, Carbon Explorer provides quantitative measures for strategies to achieve carbon-optimal settings by minimizing the overall carbon footprint, including both operational and embodied carbon footprint of the solution space holistically (Figure 2-right). Carbon Explorer demonstrates that, depending on geographic locations, carbon-optimal strategies vary from one to another. Furthermore, depending on current sustainability investments and projected renewable energy availability in the near or further future, Carbon Explorer can guide carbon-free strategies at different time granularities to achieve carbon footprint optimality as well.

A holistic approach in designing a 24/7 operational carbon-free datacenter requires multiple important components: (1) data collection and evaluation at a fine, hourly granularity across power grids at different geographic locations; (2) fair, comparative evaluation of different alternative solutions; and (3) consideration of both operational and embodied carbon footprint in the analyses.

Specifically, to prepare the inputs to the Carbon Explorer framework, we first collect hourly power draw of Meta datacenters for all of the regions within the United States. We also prepare hourly energy generation data for every geographic region at the Balancing Authority (BA) level, where Meta datacenter fleets locate at. Table I summarizes the datacenter locations and the corresponding BA electricity providers. At a high level, while datacenter power demand exhibits daily power load fluctuations, the fluctuation is relatively insignificant in the context of renewable energy availability over a day. Section III provides a detailed characterization analysis for industry-scale datacenter power demand-supply scenarios and the resulting carbon intensities.

We evaluate three distinct solutions to achieve carbonfree datacenters, explained in detail in Section IV. Shifting to renewable energy through power purchase agreements is considered a commonly-used, state-of-the-art mechanism. In addition, the computing industry has started to increase renewable infrastructure development directly at the power grids where hyperscale datacenter fleets are located at. Next, energy storage deployment is considered a promising way to handle the intermittent nature of renewable energy availability. While modern datacenters today do not deploy batteries for the purpose of carbon footprint optimization yet, batteries have been used in hyperscale datacenters for power capping [30], [45] and/or power outages. As energy storage technologies, such as Lithium-Ion batteries, mature and become cost-effective for large-scale deployment, the computing industry is exploring on-site energy storage deployment. On-site energy storage installment not only exposes carbon-free datacenter optimization opportunities but can also help de-carbonize power grids. Finally, we consider computation shifting potential by taking into account application delay-tolerance characteristics.

All three solutions — renewable deployment, energy storage deployment, and computation shifting — come with unique

design tradeoffs. Renewable infrastructure deployment is limited by geographic renewable energy availability and comes with varying degrees of energy generation efficiencies as well as manufacturing carbon emission overhead whereas on-site energy storage deployment demands space and comes with environmental implications. On the other hand, computation shifting is limited by the amount of "idle" server capacities. To increase its computation shifting potential, datacenters will have to over-provision compute capacities, incurring nonnegligible additional server manufacturing cost [22]. Section IV examines each solution in depth by taking a quantitative approach.

Last but not least, Carbon Explorer provides a comprehensive design space exploration and guideline for ways to achieve 24/7 operational carbon-free computing. Taking a step further, Carbon Explorer also demonstrates strategies toward carbon-optimal datacenters. Section V illustrates the distinct solution space for datacenters situated at different geographic regions.

III. DATACENTER POWER DEMAND AND SUPPLY CHARACTERISTICS

The first step in designing a carbon aware datacenter is to understand the datacenter power demand and renewable energy supply at fine granularity. Table I lists datacenter locations of Meta and its renewable energy investments in its local grids, each identified by the balancing authority [9]. Meta 's total renewable investments is nearly six Gigawatts across various locations.

TABLE I
META 'S DATACENTER LOCATIONS IN THE U.S. AND
REGIONAL RENEWABLE INVESTMENTS [9]

Location	Balancing	Renewable Investment [MW]		
Location	Authority	Solar	Wind	Total
1. Sarpy County, Nebraska (NB)	SWPP	0	515	515
2. Prineville, Oregon (OR)	BPAT	100	0	100
3. Eagle Mountain, Utah (UT)	PACE	694	239	933
4. Los Lunas, New Mexico (NM)	PNM	420	215	635
5. Fort Worth, Texas (TX)	ERCO	300	404	704
6. DeKalb, Illinois (IL)	PJM			
7. Henrico, Virginia (VA)	PJM	840	309	1149
8. New Albany, Ohio (OH)	PJM			
9. Forest City, North Carolina (NC)	DUK	410	0	410
10. Altoona, Iowa (IA)	MISO	0	141	141
11. Newton County, Georgia (GA)	SOCO	425	0	425
12. Gallatin, Tennessee (TN)	TVA	742	0	742
13. Huntsville, Alabama (AL)	TVA			
	Total	1823	3931	5754

In this paper, we identify and evaluate three representative regions that differ in the availability of renewable generation majorly wind, majorly solar, and mix of solar and wind. Out of the ten regions, three of them (BPAT, MISO, SWPP) belong

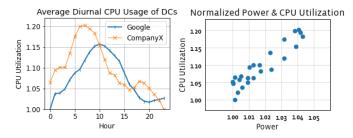


Fig. 3. [left] Hourly DC CPU fluctuations of Meta and Google DCs. [right] Hourly CPU Utilization and Power correlation of Meta DCs.

to majorly wind, three of them majorly solar (DUK, SOCO, TVA) and four of them belong to the mixed solar and wind category (ERCO, PACE, PJM, PNM).

In our power supply characteristic analysis, we draw data from the Energy Information Administration (EIA) Hourly Grid Monitor, which provides a centralized and comprehensive source for operating data for the electric power grids in the lower 48 states of the United States [62]. The monitor was launched in late 2019 and data is updated with new generation statistics every hour. EIA collects the data from balancing authorities (BAs) that operate the grid and are responsible for maintaining the electricity balance within its region. They achieve this balance by controlling the generation and transmission of electricity throughout its own region, and between neighboring authorities.

A. Datacenter Power Demand Characteristics

Meta has built hyperscale datacenters across the globe with different capacities. Due to variations in user activity, these datacenters typically exhibit diurnal load patterns and peaks during special events (e.g. holidays). Figure 3 shows the diurnal usage of Meta and Google datacenters. CPU utilization and power of Meta data is averaged over a three month period. In terms of CPU utilization, average daily swings are about 20%. Note that this is average utilization of all DCs and daily swings of individual DCs can be higher. For Google DCs, according to Google Borg traces [60], the difference between the peak and the lowest point of CPU usage is 15% on average. In terms of power draw swings, the difference between power peaks and valleys during the day is around 4%, on average.

Diurnal patterns from interactive computation do not translate directly into power patterns, in part, because datacenters schedule workloads that flatten power demand. Flexible jobs are scheduled to reduce demand during peak hours and utilize servers during off-peak times. For example, over-provisioned server capacities for web-tier services can be freed up during off-peak hours by up-to 25% [57], providing opportunistic server capacities for delay-tolerant use cases. Such schedules increase power utilization, amortizing infrastructure costs for the facility, power delivery, and servers [15]. Existing scheduling techniques to flatten power demand has significant implications for carbon-free computing: energy variations will arise primarily from supply but not demand.

Computation shifting to modulate datacenter power is possible because workloads exhibit different flexibility levels and

come with distinct service level objectives (SLOs). The highest priority, user-facing services require real-time response. Latency-tolerant workloads, such as batch and AI training jobs [57], [67], target specific SLO categories that include 4-, 8- and 24-hour completion times. Google has reported that flexible jobs with 24-hour completion SLOs make up about 40% of the Borg scheduler's jobs [60]. This flexibility in workloads permits carbon-aware workload scheduling mechanisms as well.

B. Datacenter Power Supply Characteristics

Figure 4 presents three scenarios that describe how datacenters could consume energy from rapidly evolving power grids. Renewable generation, with wind and solar, increasingly supplements or supplants traditional generation with natural gas and coal. Datacenter operators increasingly collaborate with utility providers to invest in renewable energy on the grids that power the datacenters by purchasing energy with sophisticated accounting frameworks that track renewable energy credits. Together, these strategies represent the state-ofthe-art in reducing a datacenter's operational carbon footprint for Net Zero commitments [14], [26], [29].

Scenario 1 – Grid Mix. The datacenter consumes energy from the grid and its carbon intensity depends on generating assets. Utility providers deploy a mix of electricity generating assets that define its dispatch stack, the order in which assets are activated as demand for electricity increases. Assets at the front of the dispatch stack incur the smallest marginal (fuel) costs. These assets include renewables. Although solar, wind, and hydro energy require significant capital costs, they incur modest operating costs because sun, wind, and water are free. Assets deeper in the dispatch stack are activated as electricity demand increases. These assets include brown energy sources that consume relatively expensive coal, gas, and oil.

The carbon intensity of grid electricity depends on supply from its dispatch stack and demand for its electricity, both of which vary across time. Figure 4-Case 1 illustrates the dispatch stack and variations across time, highlighting the difficulty of environmentally sustainable computing using grid energy alone. Carbon-intensive fuels, such as gas as well as coal and oil in some regions, remain a large share of the total despite recent advances in renewable and carbon-free generation with solar and wind. Wind and solar generate an order of magnitude fewer units of CO2 than natural gas and oil. Table II details the carbon intensity of electricity sources used in this paper [61]. Note that we refer to wind and solar as "carbon-free" energy sources throughout the paper but wind and solar has some trace amount operational carbon intensity.

Scenario 2 – Net Zero. Datacenter operators invest in renewable generation, such as wind and solar, and implement power purchase agreements (PPAs) to reduce datacenter exposure to the grid's carbon intensity. PPAs link renewable energy credits (RECs) with a specific source of energy and issue, e.g., one certificate for every MWh generated [13], [18], [27].

With RECs, the energy consumed is much greener than the energy offered by the grid. The grid's energy mix is

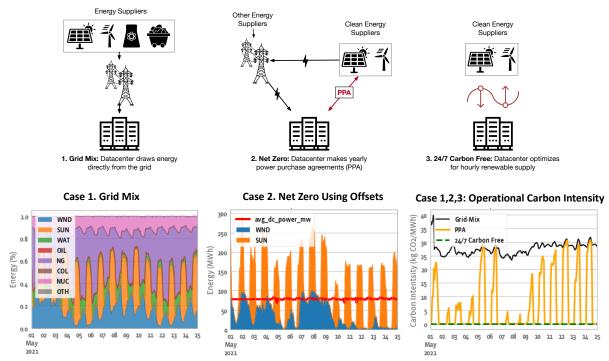


Fig. 4. [Top] Illustration of datacenter power supply scenarios: (1) Grid Mix, (2) Net Zero Using Offsets, (3) 24/7 Carbon Free. [Bottom] Case (1) Energy source mix in California grid. Case (2) Datacenter power demand and corresponding renewable investments to achieve Net Zero operational carbon free. Case (1&2&3) Comparison of operational carbon intensity of the three scenarios.

TABLE II
OPERATIONAL CARBON INTENSITY OF ELECTRICITY SOURCES

Type	gCO2eq/kWh	Type	gCO2eq/kWh
Wind	11	Natural Gas	490
Solar	41	Coal	820
Water	24	Nuclear	12
Oil	650	Other (Biofuels etc.)	230

determined by the utility provider's dispatch stack and portfolio of generating assets [6]. But the datacenter's energy mix is determined by its pre-negotiated PPAs, which deliver carbon-free energy, and any additional purchases at time-ofuse, which deliver carbon-intensive energy from the broader grid. Ideally, the latter is a small fraction of the total. Given data center operators' investments in renewable energy, most energy consumption may be matched and therefore is carbonfree; however during the remaining times energy consumption is as carbon-intensive as the grid supply [19].

Figure 4-Case 2 illustrates an example of how PPAs enable Net Zero computing. Wind and solar energy generation varies across days even as datacenter energy consumption is relatively constant. Renewable energy credits are issued as wind and solar energy is generated. At the end of the month (and end of the year), the total amount of energy generated and credits issued is greater than the total amount of energy consumed. Thus, datacenters achieve a Net Zero carbon footprint.

Scenario 3 – 24/7 Carbon Free. In addition to installing renewable energy, we must address the gaps in the intermittent renewable energy generation. Figure 5 highlights variability across time ((a) Yearly Average; (b) Highest 10 Days; (c)

Lowest 10 Days) and geography [62]. Three selected DC regions (Oregon, BPAT; North Carolina, DUK; Utah, PACE) from each category is shown: majorly wind, majorly solar, and mix of solar and wind region. On average, wind and solar installations provide significant supply, but averages obscure high variance across time. For the BPAT balancing authority, the best ten days of the year offer approximately $2.5 \times$ more renewable energy than the average whereas the worst days offer very little. Histograms in Figure 5-(d) quantify this variance, illustrating uncertainty in wind and solar supply.

Variable supplies of carbon-free energy require strategies—energy storage and demand response scheduling—during periods of scarcity. Energy storage mitigates variations in renewable energy supply by providing carbon-free energy when solar and wind cannot [48], [49]. Datacenters modulate demand for energy based on signals about renewable energy generation. Signals could come in the form of utility surcharges or credits when the datacenter consumes or reduces its energy demand during various times of day [44]. Signals can also come from utility providers' generation statistics that describe the mix of green and brown energy across time and geographic locations. The most informative signals would communicate hourly variations in energy demand and supply.

Variable energy supplies may also produce new opportunities—dynamic power pricing—during periods of abundance. As solar and wind farms proliferate, peaks and valleys in energy supply will become increasingly extreme. Utility providers will find it increasingly difficult to match its supply to consumer's demand. For example, California's renewable sources can generate much more electricity than

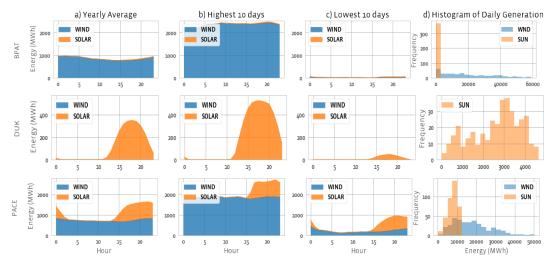


Fig. 5. Figure shows hourly (left three plots) and daily (rightmost plot) fluctuations of wind and solar generation in BPAT (for Oregon DCs), DUK (for North Carolina DC) and PACE (for Utah DC) balancing authorities which are composed of majorly wind, solar-only and a mix of wind and solar energy correspondingly. The data is averaged over the entire year of 2020.

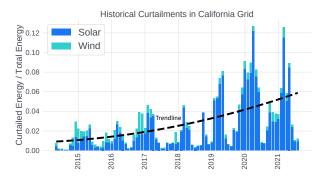


Fig. 6. Wind and solar curtailments have been increasing with the renewables on the California grid [4].

needed in the middle of the day [4]. Curtailments manage excess supply by reducing generation from renewable sources [7], [8], [37]. Figure 6 indicates that, since 2015 the curtailed gap between supply and demand has grown steadily as wind and solar capacity has increased. In 2021, curtailed energy reached 6% of the total generated renewable energy in the California grid which has significantly higher percentage of renewable electricity compared to the U.S. average (33% vs 20% in 2020 [5], [58]). This indicates that it is becoming increasingly complicated to utilize peak renewable energy generations due to the high variance. When supply exceeds demand, only generators with the lowest prices can supply energy to the grid. Prices can be zero or even negative because inputs to wind/solar farms are free and generators often receive government subsidies [11], [72]. As a result, grids may offer lower time-of-use energy prices and incentivize datacenters to defer computation to periods of abundant renewable energy.

In summary, the Grid Mix scenario provides a baseline and is particularly relevant for smaller datacenters that have not yet customized their energy purchases. The Net Zero scenario describes how investments in renewable energy significantly reduce the carbon intensity of datacenter operations. Finally, the 24/7 scenario describes how additional investment and demand response schedulers could further reduce carbon intensity. Figure 4-Case 1&2&3 compares the carbon intensity of these three energy supply scenarios. We will show how datacenter operators that progress along these scenarios would make significant advances toward carbon-free operations on an hourly basis in Section IV. Perhaps equally important, our proposed framework — Carbon Explorer — enables datacenter operators to devise coordinated strategies for deploying renewable energy generation, energy storage, and demand response scheduling.

IV. STRATEGIES FOR CARBON FREE COMPUTING

A 24/7 operational carbon free datacenter must implement a portfolio of complementary solutions to achieve carbon free computing efficiently and resiliently. In addition to renewable energy investment, Carbon Explorer implements energy storage deployment and carbon aware scheduling as complementary solutions and analyze the carbon footprint trade-offs quantitatively. In this section, we present the three important strategies to enable 24/7 carbon-free computing: Renewable investments (Section IV-A); Battery deployment (Section IV-B); Carbon aware scheduling (CAS) (Section IV-C).

A. Renewable Investments

As we show in Section III, inherent variations in solar and wind makes powering a datacenter solely on renewable energy challenging. In this section, we quantify the amount of solar and wind investments it takes for datacenters situated in different geographic regions to increase their hourly renewable coverage from relying on the grid-mix towards achieving 100% renewable at every hour. We also include current renewable investments of Meta in this analysis.

Wind and solar power generation suitability varies region by region. For example, the US Midwest is more favorable

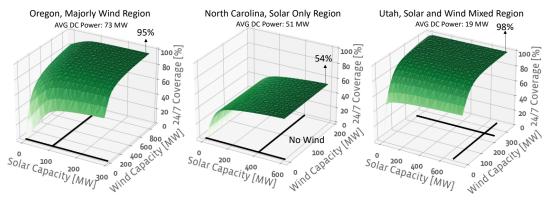


Fig. 7. 24/7 coverage with varying amount of wind and solar investments. Black lines show Meta 's renewable investment amount in the corresponding region.

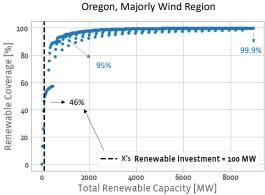


Fig. 8. 24/7 coverage with different renewable investments highlighting the long tail. Each point represents a different solar + wind capacity combination.

for wind-based power generation whereas the Southeast is for solar-based. Therefore, there are geographic regions where Meta invests in wind generation only (such as Iowa), solar only (such as Carolinas, Tennessee), and a mix of wind and solar (such as Virginia). We cluster the regions into three major renewable investment categories in terms of their renewable generation sources: majorly wind, majorly solar, and mixed. Meta 's investments are generally in the same categoras the renewable energy generation profiles of the local grids. Only BPAT region poses an exception to this categorization: despite being a majorly wind location, Meta 's investments in Oregon are only in solar power.

Over all the renewable investment profiles, relying solely on renewable generation brings diminishing returns in terms of 24/7 coverage. Figure 7 shows the 24/7 renewable coverage percentage of datacenters (the z-axis) with different wind (the x-axis) and solar (the y-axis) investment amounts from the three selected regions, one from each category. The 24/7 renewable coverage percentage is defined as the percentage of hours during the year where the datacenter is powered by renewable energy. As the 24/7 coverage gets closer to 100%, the curve saturates. For majorly wind regions, like Oregon, day-to-day fluctuations are higher, which makes the amount of investments needed to supply for the minimum much higher. Meta 's renewable investments are highlighted with black lines on the bottom of Figure 7. While these investments in each region help achieve Net-Zero, their 24/7 coverage percentages

are 46%, 51% and 98.8% correspondingly.

There is a long tail to reach 100% 24/7 coverage. As highlighted in Figure 8, it takes more than five times more renewable investments to go from 95% to 99.9% than to go from 0% to 95%. Furthermore, for solar-only regions, like North Carolina, it is impossible to increase the overall renewable coverage beyond 50% because solar power is only available during the daytime. Therefore, other solutions to complement renewable power, such as using energy storage and/or computation shifting, is essential. On regions with mixed solar and wind, like Utah, there is still diminishing return; however, the tail is shorter. Due to space limitation, we are unable to show profiles of every datacenter location in the paper. We note the different locations in the same renewable investment category have similar profiles.

B. Battery Storage

The efficiency improvement for battery systems in the last decade has made lithium-ion batteries (LIB) one of the most common energy storage systems, offering high capacity and energy density [10]. Further, as the technology matures, LIB becomes cost-effective and is used as a common storage medium for renewable energy [68]. Therefore, batteries play an important role to reach 24/7 carbon free computing. This section evaluates the deployment of batteries on datacenters to complement the renewable energy strategy — during the times when there is lack of renewable supply.

Datacenters already deploy batteries to prevent interruption of services during maintenance or during power failures, such as when switching to diesel generator power after a utility power failure [46]. In our case, batteries are deployed on the datacenter site, in order to reduce datacenter's carbon footprint. Whenever there is excess renewable supply (i.e. when the amount of energy produced by the renewable deployment is larger than datacenter's demand), batteries will be charged. Whenever there is lack of renewable supply (i.e. when the amount of energy produced by the renewable deployment is smaller than datacenter's demand), batteries will be discharged to power the datacenter. We assume, at the end of three consecutive days, the deployed batteries should be recharged fully; otherwise, we consider that as an impractical battery

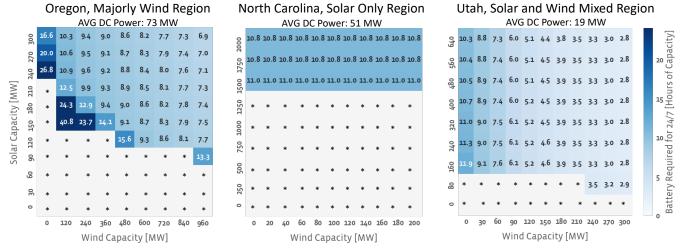


Fig. 9. How much battery needs to be deployed for 24/7 renewable energy?

deployment capacity. Note, while batteries can be deployed in the Grid-Mix scenario described in Section III, the benefits of this approach are marginal and therefore we do not consider this solution here.

Figure 9 shows the amount of energy storage capacity required, in terms of hours, to reach 24/7 renewable energy coverage at different solar and wind capacities for the three selected datacenter regions. We mark the impractical battery deployment capacity with a '*' symbol in Figure 9. Due to extremely high day-to-day renewable fluctuations in the wind only region Oregon, the battery deployment requirements per MW of renewable investment to reach 24/7 is the highest. This is because there are full days with extremely low wind power. For solar only regions, like North Carolina, on average at least 11 hours of capacity is required to reach 24/7. It is easiest to reach 24/7 with batteries in mixed solar and wind regions, like Utah, with less variable day-to-day fluctuations. For example, by adding 3.3 hours of battery capacity, Meta 's Utah datacenter can reach 24/7 carbon-free operational energy.

C. Carbon Aware Scheduling

Delay tolerant workloads provide excellent carbon-aware scheduling opportunities to achieve 24/7 carbon-free computing by shifting the workloads from times when the carbon intensity of the electricity source is high to times when carbon intensity is low. Workloads in hyperscale datacenters are commonly composed into tiers in terms of their Service Level Objectives (SLOs). Higher tier jobs are latency sensitive and require high availability. On the other hand, lower tiers can tolerate delays by nature. Examples to such temporally flexible workloads include AI model training, data processing pipelines, and offline video processing. Google Borg traces show that a significant fraction of the jobs submitted to the Borg scheduler are in the free and best-effort-batch tiers with weak SLAs [60]. Data warehouse jobs at Meta show similar characteristics — 60% of the batch jobs in the data warehouse needs to land with daily consistency or their landing time is not important.

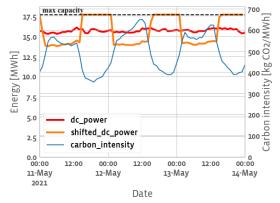


Fig. 10. Carbon aware scheduling illustration for the Utah DC.

Carbon aware scheduling mechanism can make the peak power draw higher than the peaks in the baseline power draw. Shifting computation in time can require surplus in server capacity to sustain more computation when carbon-free/lowcarbon energy is abundant. The need for surplus capacity reveals an interesting design trade-off space between operational and capital decisions. From an operations perspective, over-provisioned servers mitigates the data center's carbon footprint by permitting demand response and reducing the carbon intensity of its energy. However, from the capital perspective, over-provisioned servers increase the overall carbon footprint by increasing embodied carbon emissions from hardware manufacturing [22]. Therefore, there is a fine balance between operational and capital expenditures. Furthermore, energy-proportionality is desirable [2]. Server power can be accurately modeled as a linear function of utilization with the y-intercept denoting a server's idle power. To illustrate energy-proportionality, we have demonstrated the correlation between the datacenter-level power consumption of Meta and CPU utilization of the DCs in Section III (Figure 3).

Carbon Aware Scheduling with Grid Mix. Figure 10 illustrates an example of a carbon aware scheduling mechanism over three days of duration. In this time frame, blue line shows that carbon intensity of the grid varies depending on the hour

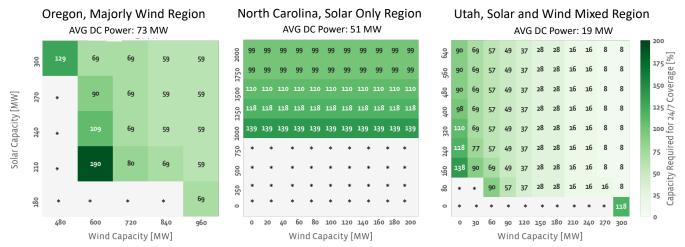


Fig. 11. Scenario 3: Carbon aware scheduling for 24/7.

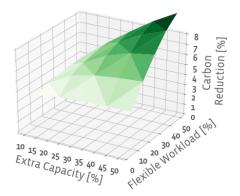


Fig. 12. Carbon aware scheduling for the Utah DC with grid mix.

of the day. The red line shows the baseline DC power draw, when carbon aware scheduling is not applied and orange line represents the power draw when carbon aware scheduling is applied. The maximum allowed power capacity of the DC is assumed to be 17.6 MW and 10% of the workloads running every hour are flexible to finish within a day. Given these two constraints, carbon aware scheduling mechanism moves the workloads from high carbon intense times to the low carbon intensity times of the day. Note that this is a best-case evaluation of workload shifting, where the shifted DC power sits at the maximum capacity. When applied to production workloads, shifted DC power may not be perfectly shifted. Depending on the extra capacity available and the amount of flexible workloads in the DC load, operational carbon reduction that carbon aware scheduling can achieve varies. Figure 12 shows that, for the Utah datacenter, carbon aware scheduling can achieve up to 8% operational carbon reduction with 50% extra capacity and 50% flexible workload ratio.

Carbon Aware Scheduling for 24/7 with Additional Servers. Similar to the Grid-Mix scenario, carbon aware scheduling can be used to achieve 24/7 renewable by shifting workloads from times when there is lack of renewable energy to times with excess supply. Figure 11 shows how much additional server capacity, in terms of percentage of the existing server capacity, is required to achieve 24/7 carbon

free computing. We define capacity in terms of datacenter power (e.g., 1MW of spare capacity in a 20MW datacenter) and assume the capacity of the DC is the maximum power consumed within the time of evaluation (three months [May-July 2021]). Any extra capacity needed beyond the maximum power is counted as additional capacity required. Moreover, all workloads are assumed to be flexible to shift. Analysis shows that the additional capacity required to reach to 24/7 varies between 8% to over 100% (i.e. doubling the datacenter server capacity). Alternative to deploying additional capacity, datacenters might Turbo Boost its current deployment of processors, increasing compute throughput without increasing capital costs or embodied carbon footprints.

V. HOLISTIC DESIGN EXPLORATION

Reaching 24/7 operational carbon free computing often comes with additional, non-negligible embodied carbon cost. Thus, to achieve carbon-efficient datacenters, we must consider *both* operational and embodied carbon footprint holistically when minimizing the overall carbon footprint of datacenters. Carbon Explorer provides *a quantitative measure* to achieve 24/7 carbon free computing in the most carbon efficient way, by taking into account the overall carbon footprint of renewable investments (Section IV-A), battery storage (Section IV-B), and carbon-aware scheduling (Section IV-C).

A. Embodided Carbon Footprint Consideration

Renewables. According to the National Renewable Energy Laboratory (NREL), the manufacturing (or embodied) carbon footprint of wind turbine ranges from 10-15 grams of CO₂ per kWh whereas the manufacturing footprint of a solar farm ranges from 40-70 grams of CO₂ per kWh [23]. These numbers are derived from a life cycle analysis and accounts for its manufacturing cost and the expected amount of energy generated over the expected lifetime.

Batteries. The manufacturing footprint of lithium-ion batteries ranges from 74 to 134 kilograms of CO₂ per KWh of battery capacity [12], [52]. The footprint includes material

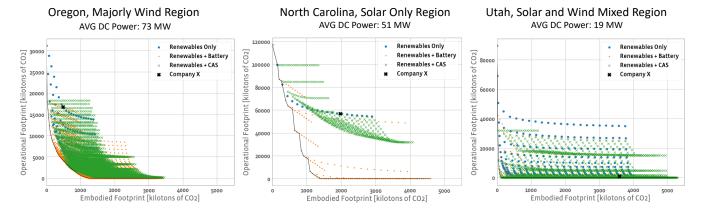


Fig. 13. Operational and embodied footprint of the three solutions.

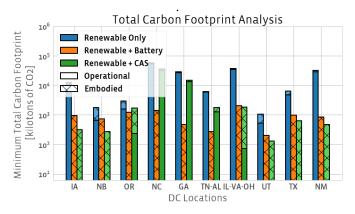


Fig. 14. Minimum total footprint of the three solutions broken down to operational and embodied components. (See Table I for DC location details.)

production, cell production and assembly, as well as end-of-life processing for the batteries, which is a necessary and challenging task [68]. Lifetime of the battery is calculated in terms of the number of discharge cycles. Utility-scale batteries, like Tesla's Powerpack, last between 3000-4000 cycles [55]. In this study, we assume one cycle will be used per day and hence the lifetime of the battery is around 10 years.

Servers. The manufacturing footprint of servers is estimated using an HPE server as a proxy. The manufacturing footprint of a HPE ProLiant DL360 Gen10 server is 744.5 kg eq CO₂ [24]. This server is a single socket CPU server with 48 GB DRAM and with the Thermal Design Power (TDP) rating of 85 Watts. The carbon measurements include its mainboard, SSD, daugtherboard, enclosure, fans, transport and assembly. We use five years as the expected server lifetime.

B. 24/7 Carbon Free Datacenters: A Holistic Analysis

There are multiple strategies to achieve operational carbon free datacenters. Depending on datacenter locations, Carbon Explorer provides a quantitative measure for each strategy that comes with unique embodied carbon cost tradeoffs—the most carbon cost-effective strategy varies. Figure 13 quantifies the carbon footprint reduction effectiveness across three strategies: an exclusive renewable only investment profile (Renewables Only), renewable investment with batteries (Renewables + Battery) and renewable investment with carbon

aware scheduling (Renewables + CAS). The x-axis depicts the manufacturing carbon emissions whereas the y-axis represents the operational carbon footprint. In this evaluation, we assume 40% of datacenter jobs are delay-tolerant — a realistic flexible workload ratio for carbon aware scheduling [60].

Using Carbon Explorer to identify most carbon-efficient strategies to achieve operational carbon free datacenters, Figure 14 illustrates the minimum total footprint of the three solutions, including *both* operational and embodied carbon cost (depicted using solid- and cross-pattern bars, respectively). Our first observation from the analysis is that *Renewables Only* results in the highest amount of total carbon for all the datacenter regions (the horizontal axis). This evaluation confirms our initial hypothesis that we must have complementary solutions to wind and solar deployments. In fact, the renewable coverage of the carbon optimal solution with the *Renewables-Only* strategy ranges from 53% to 99% for the different regions. As expected, solar only regions (i.e. NC, GA, TN, AL) generally result in the highest footprint with this strategy since solar energy is only available during daytime.

Secondly, (*Renewables* + *Battery*) and carbon aware scheduling (*Renewables* + *CAS*) can be justified by their operational carbon reduction in all of the datacenter locations. Batteries can enable 24/7 in all the datacenter locations and reduce the need for demand response by storing and supplying carbon-free energy. The most carbon optimal way to deploy batteries is to deploy enough battery capacity to remove the operational footprint completely. *Renewables* + *Battery* strategy reduces the total footprint by an order of magnitude in all regions, with the footprint reduction being most prevalent in solar-only regions.

Thirdly, *Renewables* + *CAS* provides an alternative strategy to achieve carbon reduction. In most of the wind-only (i.e. IA, NB, OR) and hybrid regions (i.e. IL, VA, OH, UT, TX, NM), *Renewables* + *CAS* is more effective than *Renewables* + *Battery*. The additional required server capacity for CAS is in the range of 1 to 11% for the wind-only and hybrid datacenter regions, therefore *Renewables* + *CAS* is a carbon-efficient alternative to *Renewables* + *Battery* in these regions. On the other hand, since *Renewables* + *CAS* is limited by the degree of workload scheduling flexibility and relies on

additional, available server capacities, for regions like OR where there are significant number of days with near zero wind generation (see Figure 5) and for solar only regions, *Renewables* + *CAS* alone is not sufficient to reach 24/7.

In summary, the most effective solution varies depending on the renewable energy generation characteristics of the datacenter regions. Both *Renewables* + *Battery* and *Renewables* + *CAS* can offer an order of magnitude reduction in total carbon footprint of datacenters. Since batteries do not have the workload flexibility limitation like *Renewables* + *CAS*, *Renewable+Battery* achieves 100% operational coverage for all of the datacenters. Furthermore, the only viable solution to reach 24/7 for the datacenter in solar only regions is deploying batteries. Finally, *Renewables* + *CAS* offers a competitive alternative to *Renewable+Battery* in most of the wind-only and hybrid regions.

VI. DISCUSSION AND RELATED WORK

Renewable Energy. Prior academic research emphasizes renewable energy on-site at the datacenter [35]. Computation uses local, solar energy and minimizes energy consumed from the grid [16], [17]. The datacenter's power infrastructure is enhanced to switch between multiple types of local generators and microgrids [35], [36], [42]. And strategies are developed to deploy scale out servers and renewable generators in a modular fashion [32], [34]. These strategies seem sensible for edge and fog servers [33]. However, the hyperscale datacenters we study avoid many of these challenges. They do not need to manage local power generation because they have invested in renewable generation on the grid at scales that are unlikely onsite. Yet they improve sustainability through power purchase agreements. We study renewable energy across geographic locations and coordinate their installation with battery and server provisioning at scale.

Energy Storage. Batteries ensure datacenter availability but can also modulate the datacenter's demands for grid power [20], [21]. For datacenters that use renewable energy, batteries can mitigate intermittent supplies of solar and wind [38], [41]. Performance and efficiency vary with battery technology, motivating heterogeneous solutions [40], [43]. Battery aging can be mitigated by managing charge-discharge cycles and demand for stored energy [39]. We quantify energy storage required for 24/7 carbon-free computing and, without loss of generality, consider lithium-ion batteries for their attractive downward cost trajectory and acceptable ten-plus year lifetimes under simulated usage.

Battery technologies will impact data center design and management. The price of lithium-ion batteries is falling significantly, declining by 80% from 2015 to 2020 [48], [49]. These batteries have been deployed at scale and, for example, can supply 28 MW for four hours. Such operational parameters align with hyperscale datacenters, which are provisioned for 20 to 40 MW. Four hours of battery operation could significantly reduce demand response requirements from job scheduling.

Although our paper makes the case for energy storage, it does not explicitly prescribe an implementation strategy.

Datacenter operators could collaborate with utility providers to invest in batteries on the grid just as they do for wind and solar farms. Alternatively, they could deploy batteries on-site at the datacenter. Datacenter may wish to implement custom battery charge-discharge policies, which have previously been explored at much smaller scales for uninterruptible power supplies [20], [21]. Whether these policies can be implemented in the form of contracts with grid operators is to be determined.

Finally, there are potentially environmental and health risks associated with the disposal of batteries. Spent LIBs contain toxic materials including heavy metals and flammable electrolytes, and therefore they need to be properly recycled and disposed in order not to cause contamination of the soil, water and air [51], [69]. This is another aspect that needs consideration when making large-scale battery deployments.

Carbon-Aware Scheduling. Time-series analysis accurately forecasts renewable supplies and datacenter demands for energy. Forecasts permit optimizing schedules of flexible jobs in response to energy supply [70]. Optimization objectives have accounted for electricity prices [44], carbon prices in cap-and-trade markets [31], the carbon-intensity of grid energy [50], and service quality [28]. Timely energy data is necessary for intelligent scheduling [3], [64]. We perform offline analyses to defer flexible computation and explore the design space for 24/7 carbon-free computing. A future implementation would benefit from prior schedulers.

Power Transmission. In addition to energy storage technologies, transmitting electricity generated from renewables is another potentially viable option. The recent technology breakthroughs in renewable energy generation, energy storage, and electricity transmission are energizing novel infrastructure development and deployment [66], such as, transmitting solar power from Australia underneath an ocean to Singapore [53]. High-voltage direct current (HVDC) transmission technology is becoming an attractive option to transmit electricity between renewable generation sites and power grids and for transnational grids [56], [63]. While the HVDC technology has seen significant efficiency and energy capacity transmission improvement, it is currently less efficient as compared to data/computation scheduling across data centers in different geographic locations (by roughly two orders of magnitude). Thus, *locality* — from the perspectives of where energy is generated and where data resides — is important to keep in mind for the near future. As power transmission technologies becomes increasingly cost-effective, renewable energy availability will become more geographically inclusive. The impact of the power transmission dimension can be taken into the Carbon Explorer design space to understand the dynamics.

VII. CONCLUSION

This paper presents Carbon Explorer — a design space exploration tool to enable carbon-optimal investment strategies. Carbon Explorer determines carbon-optimal settings across the dimensions of investments on various renewable energy types, the amount of energy storage, and carbon-aware computation shifting by considering geographically-dependent renewable

energy availability characteristics and computation demand patterns at the data center scale. Carbon Explorer demonstrates that, depending on graphical locations, carbon-optimal strategies vary from *Renewable and CAS* for data centers where plenty of wind-based renewable energy is available, to *Renewable and Battery* where solar-based renewable energy is the primary investment. We hope Carbon Explorer can guide future sustainability investments to achieve operational and embodied carbon footprint optimality.

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