Google

Moving toward 24x7 Carbon-Free Energy at Google Data Centers: Progress and Insights

Introduction

In recent years, Google has become the world's largest corporate buyer of renewable energy. In 2017 alone, we purchased more than seven billion kilowatt-hours of electricity (roughly as much as is used yearly by the state of Rhode Island[1]) from solar and wind farms that were built specifically for Google. This enabled us to match 100% of our annual electricity consumption through direct purchases of renewable energy; we are the first company of our size to do so.

Reaching our 100% renewable energy purchasing goal was an important milestone, and we will continue to increase our purchases of renewable energy as our operations grow. However, it is also just the beginning. It represents a head start toward achieving a much greater, longer-term challenge: **sourcing carbon-free energy for our operations on a 24x7 basis.**

Meeting this challenge requires sourcing enough carbon-free energy to match our electricity consumption *in all places, at all times*. Such an approach looks markedly different from the status quo, which, despite our large-scale procurement of renewables, still involves carbon-based power. Each Google facility is connected to its regional power grid just like any other electricity consumer; the power mix in each region usually includes some carbon-free resources (e.g. wind, solar, hydro, nuclear), but *also* carbon-based resources like coal, natural gas, and oil. Accordingly, we rely on those carbon-based resources — particularly when wind speeds or sunlight fade, and also in places where there is limited access to carbon-free energy. Carbon-free or not, around-the-clock electricity is the fuel that enables us to continuously deliver Google search results, YouTube video plays, Google Cloud Platform services, and much more without interruption.

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To address our use of carbon-based energy, we buy a surplus of renewable energy in regions or hours when solar and wind power *are* abundant. For example, we buy larger amounts of wind energy in places like the US Midwest to offset our lack of renewable energy purchases in Asia. And in some places, we buy additional solar energy during the day to compensate for our use of carbon-based energy at night. In this way, we purchase enough renewable energy to match our total annual electricity use. Our purchases directly result in more renewables being added to the grid (i.e. we adhere to high standards of project additionality[2]) and reduce CO_2 emissions. On a global and annual basis, our purchases of solar and wind energy zero out the entire carbon footprint of our electricity use. Yet this is an imperfect solution. We want to build a future where *each* Google facility is *always* matched — around the clock — with carbon-free power.

Google has multiple compelling reasons to pursue a shift to carbon-free energy sources: we strive to lead on climate change as a business imperative; we are a large electricity consumer that seeks to minimize our environmental footprint; and we are a growing business that prizes the cost-effectiveness and financial certainty of renewable power sources. In parallel to maintaining our annual 100% renewable energy purchasing goal, we recognize that fully decarbonizing the electricity sector requires 24x7 carbon-free energy. Pursuing this long-term objective is important for elevating carbon-free energy from being an important but limited element of the global electricity supply portfolio today, to a resource that fully powers our operations and ultimately the entire electric grid.

To guide Google's progress, we've analyzed how we are tracking toward 24x7 carbon-free electricity at our data center campuses, which account for the vast majority of Google's total electricity consumption. Our progress to date has primarily resulted from signing wind and solar power purchase agreements (PPAs) in pursuit of our annual 100% renewable energy match goal. Google's longstanding commitment to energy efficiency has also played a vital role: by minimizing our electricity needs, we have reduced the amount of carbon-free energy required to match our consumption. The average Google data center uses half as much energy as a typical data center, and we continue to employ innovative strategies to improve efficiency.[3]

To orient us toward achieving 24x7 carbon-free energy, it's important that we ascertain where we stand today in each region. The analysis herein marks the first time that we have examined this question in depth and is an essential step in working toward a carbon-free energy future.

In this paper, we discuss three aspects of our initial 24x7 carbon-free energy efforts:

1. A framework for evaluating how well a given data center is matched with regional 24x7 carbon-free energy
2. Examples of Google's progress on carbon-free energy at a representative selection of data center campuses
3. Insights that can guide our journey toward 24x7 carbon-free energy

I. A Framework for 24x7 Carbon-Free Energy

We define carbon-free energy as any type of electricity generation that does not directly emit carbon dioxide. This includes renewables like solar, wind, geothermal, hydropower, and biomass.[4] Nuclear power is also carbon free. In the future, our framework can be extended to other technologies, such as carbon capture and storage, that are yet to be deployed at scale but could enable carbon-free power generation from additional sources.

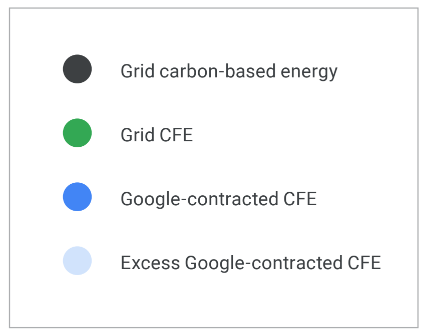
By analyzing granular energy data, we can measure how a given data center's hourly electricity use coincides with hourly carbon-free electricity supply on the regional grid.[5] This carbon-free electricity consists today of two components. The first carbon-free component is electricity that Google buys, through long-term PPAs, from wind and solar projects in a region.[6] The second carbon-free component is electricity coming from the broader regional power grid via sources like nuclear, hydropower, and renewables that Google has not directly contracted.

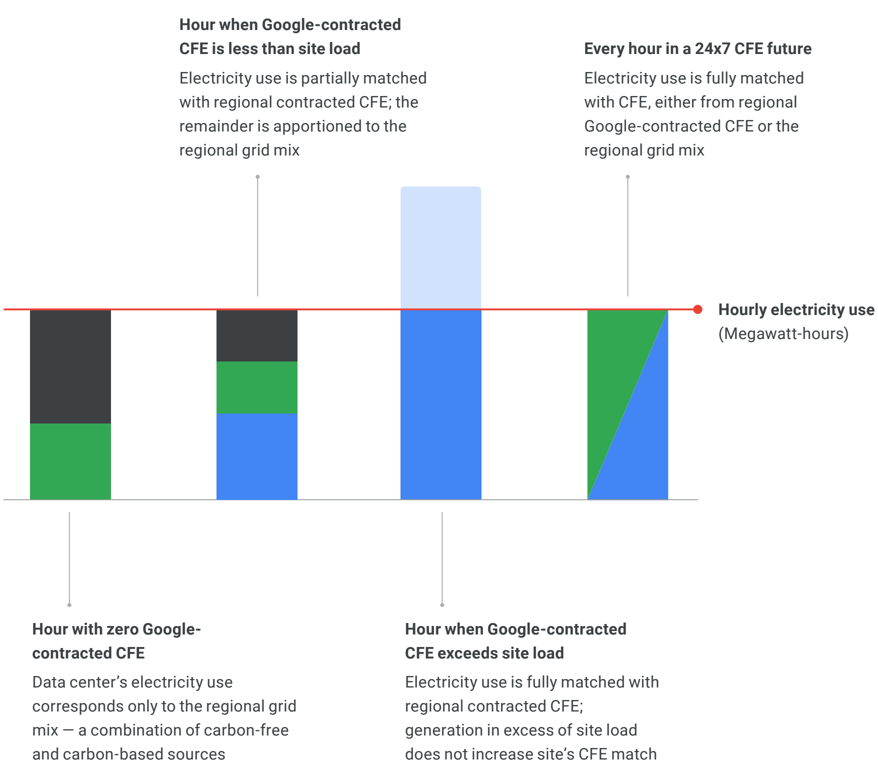
In evaluating how well a data center's electricity consumption is matched on an hourly basis with carbon-free energy, our framework first considers the renewable energy generation associated with Google's PPAs in a particular region.[7] If regional Google-purchased renewable generation in a given hour is equal to or greater than a data center's electricity load, then the data center is matched 100% with carbon-free sources for that hour. However, if Google's regional renewable generation is insufficient in a given hour to match the data center's load, then the remainder electricity is attributed to the region's grid mix. Figure 1 shows several possible scenarios for how data center electricity use can line up with regional carbon-free energy supply in a given hour.

FIG. 1

Hourly scenarios in our carbon-free energy (CFE) framework

In any given hour, a data center's energy profile takes one of the following forms:





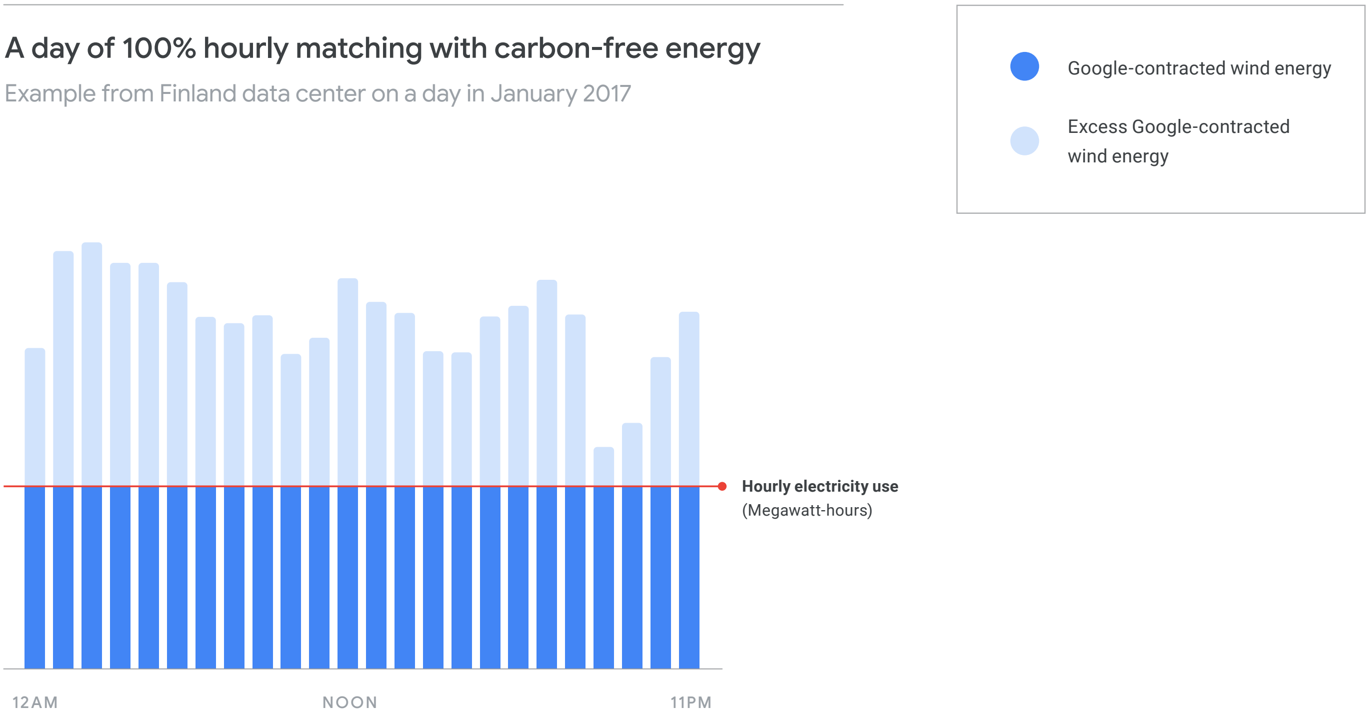
In any given hour, a region's grid mix usually consists of some carbon-free power and some carbon-based power. The grid mix can vary greatly from region to region, and also from hour to hour. For instance, the Nordic countries and the US Pacific Northwest have a highly carbon-free grid mix due to abundant hydropower, while parts of Asia and the US Southeast have a largely carbon-based mix due to fossil power plants. In the same vein, regions with outsized solar capacity often exhibit a more carbon-free grid mix during daytime than nighttime.

The carbon footprint of a data center is minimized when its hourly energy use is fully matched by regional carbon-free generation, either from Google-contracted renewables or the broader grid mix. Figure 2 depicts a fully carbon-free day in January 2017 at our Finland data center, where hourly electricity consumption was 100% matched with Google-contracted wind energy in the region. In most hours of the day, our regional wind PPAs produced approximately double the energy required to match our data center load.[8]

FIG. 2

A day of 100% hourly matching with carbon-free energy

Example from Finland data center on a day in January 2017



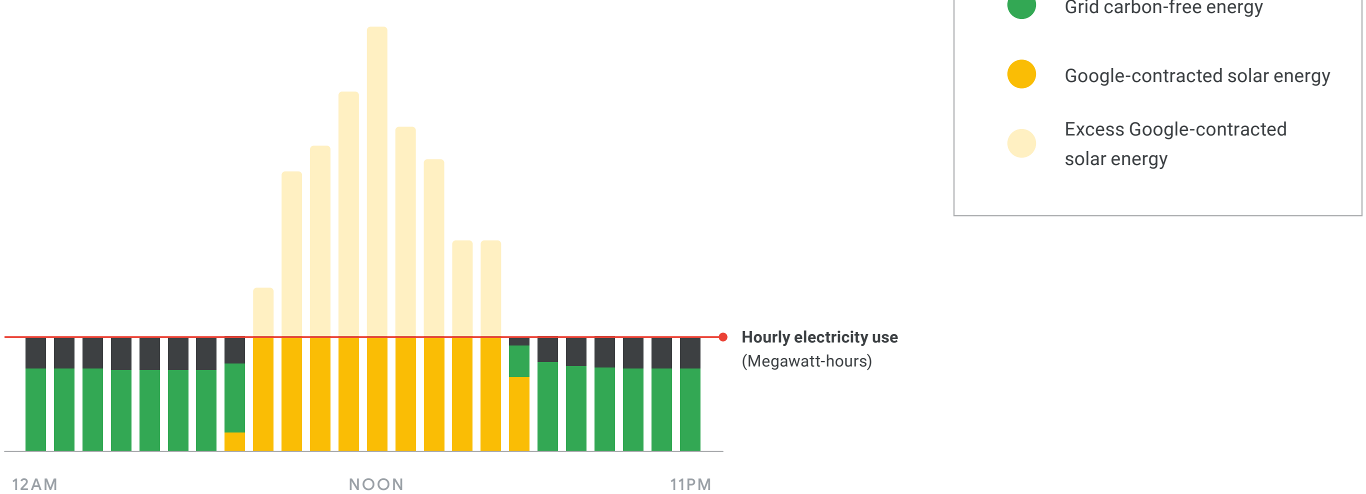
However, there is often not enough carbon-free energy available to match 100% of a data center's hourly electric load in a given hour. There are several possible factors — related to Google or the grid — that can cause an hourly shortfall in carbon-free energy. On the Google side, factors may include a dearth of Google renewable PPAs in the region; insufficient output from our existing renewable PPAs, due to low wind speeds or faint sunlight; or a lack of stored carbon-free energy to fill the gaps. On the grid side, factors may include a regional grid mix not being fully carbon free, or other technical and regulatory constraints that inhibit carbon-free energy supply. In the event of a carbon-free energy shortfall, we attribute a portion of the data center's hourly electricity consumption to carbon-based power from the regional grid.

As an example, Figure 3 shows a day in August 2017 at our data center in Quilicura, Chile, which experienced several hours of carbon-free energy deficit due to sunlight variability. During sunny hours, a Google-contracted solar farm in the region produced more than enough energy to fully match data center load; during less sunny hours, however, the data center's match with carbon-free energy fell below 100%, relying instead on the grid mix and its carbon-based content. Although excess midday solar production more than "offset" the day's total contribution from carbon-based energy, the data center failed to achieve around-the-clock 100% carbon-free matching.

FIG. 3

A day of inconsistent hourly matching with carbon-free power

Example from Chile data center on a day in August 2017



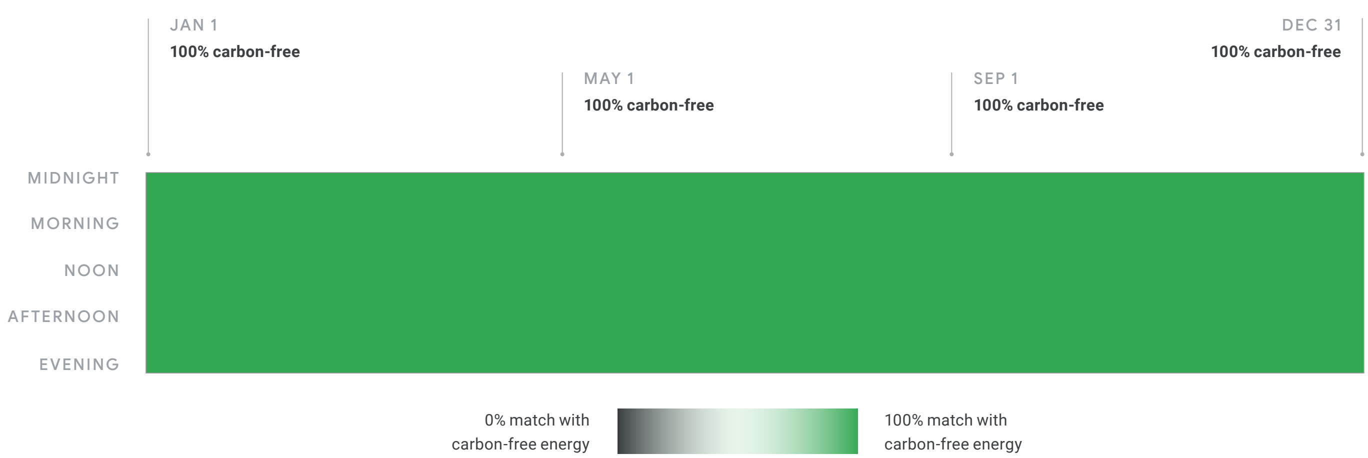
Figures 2 and 3 depict the carbon-free profile of a data center for a given *24-hour period*. But the scope of our energy challenge is bigger than any single day: we want to match each data center with carbon-free energy *in every hour of the entire year.* To capture this more expansive view, we can use a heat map that visualizes each hour of the year — all 8,760 of them — where **greener** hours represent a higher rate of carbon-free energy matching.

The heat map in Figure 4 depicts an idealized data center that is matched 100% with regional carbon-free energy in every hour of the year. Going from the rectangle's left to right, January 1st is the left edge and December 31st is the right edge; going from the rectangle's top to bottom, each day begins at midnight and elapses downward until the day is done.

FIG. 4

Every hour of electricity use at a 24x7 carbon-free data center

A data center that is 100% matched with carbon-free energy around the clock — 24 hours a day, 7 days a week, 365 days per year

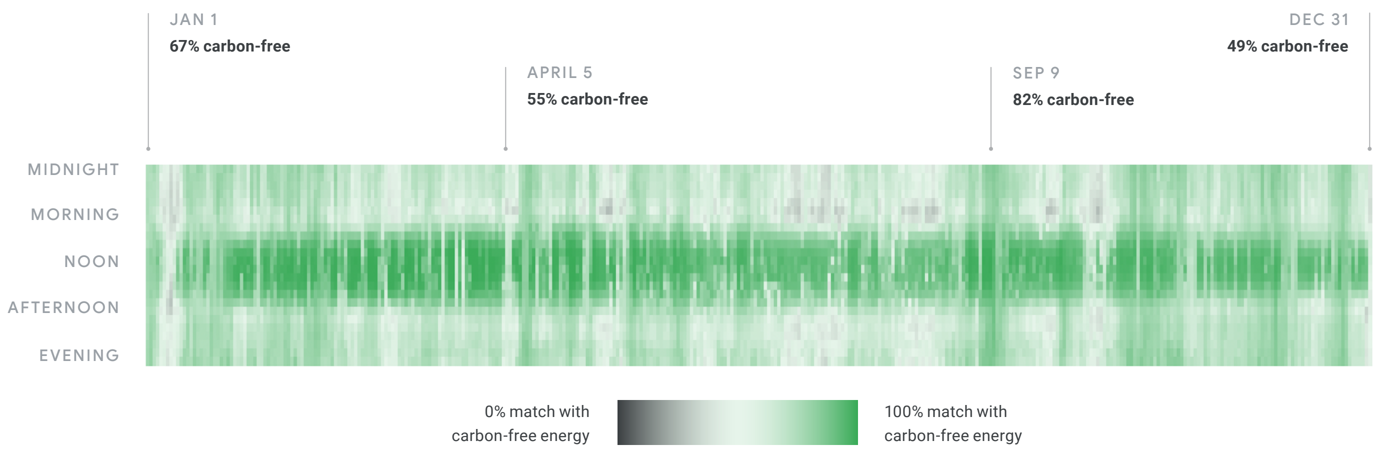


By comparison, Figure 5 depicts a real-world data center (which we'll revisit further below) that fails to reach a 100% match with carbon-free energy in any hour. Its energy profile varies throughout each day, though clearly achieves the highest rates of carbon-free energy matching during midday hours — coinciding with the availability of solar energy.

FIG. 5

Every hour of electricity use at a real-world data center

This data center's midday electricity use is matched with regional solar energy, making its carbon-free profile highest during those hours



By combining data on hourly electricity consumption and hourly regional electricity supply, the foregoing framework and visualization methods can quantify how well a given data center is matched with carbon-free energy on any time scale.

II. Examples of Google's Progress Toward 24x7 Carbon-Free Energy

Due to our efforts since 2010 to procure solar and wind power in regions where we operate (as part of our annual 100% renewable energy purchasing goal), many of our data centers have already attained a strong degree of hourly matching with regional carbon-free energy. In all data center regions where we have signed renewable PPAs, at least 65% of the local data center's electricity consumption in 2017 was matched on an hourly basis with carbon-free energy. A related finding is that in 2017, Google's fleet of solar and wind PPAs was always putting some amount of carbon-free energy onto the grid somewhere in the world. That is, in every single hour of the year, one or more Google renewable energy projects was producing power.

However, our analysis also finds that none of Google's data center campuses in 2017 was matched 24x7 with 100% carbon-free energy. Still, a few campuses — like our data center in Finland — are beginning to show what's possible.

Finland

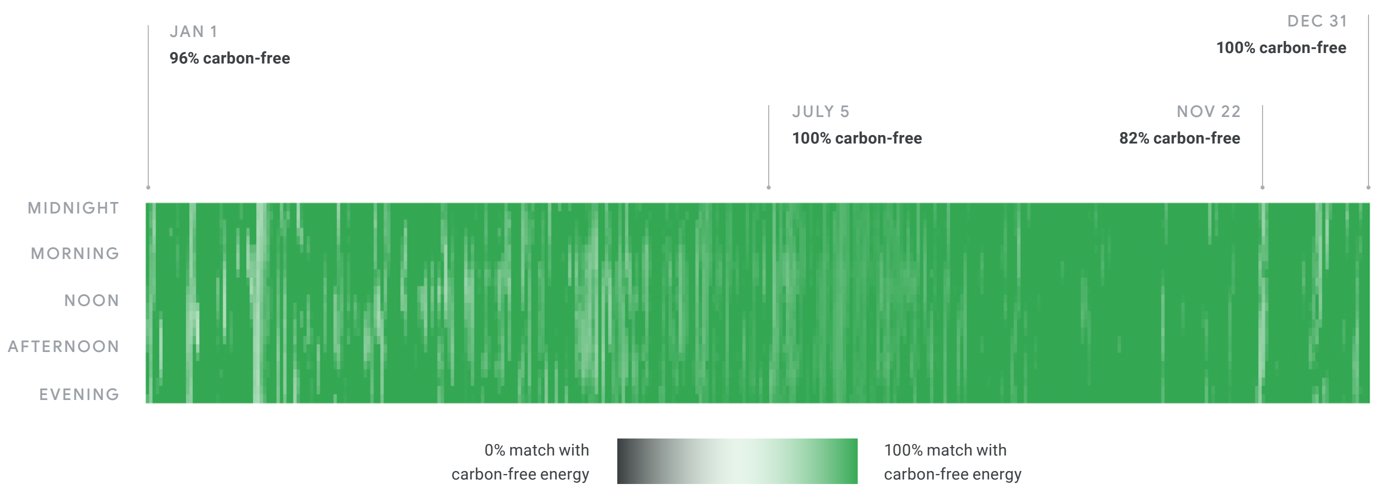
As shown below in Figure 6, our Hamina, Finland, data center's electricity consumption in 2017 was strongly matched on an hourly basis with regional carbon-free energy. Overall, 97% of the data center's electricity consumption was matched with such sources. We can attribute this to a couple factors. First, thanks to a competitive electricity market structure in the Nordics, Google has been able to sign multiple wind energy PPAs in the region.[9] These PPAs deliver a substantial amount of electricity to the grid and, on an hourly basis, frequently produce more energy than our Finnish data center consumes. Second, Finland's power grid has an abundance of other carbon-free energy sources like nuclear, hydropower, and biomass.

FIG. 6

Every hour of electricity use at Finland data center

Google's purchases of wind power in the Nordic region, combined with significant nuclear and hydropower on the grid, mean that in most hours this data center is 100% matched with carbon-free energy

Overall in 2017, 97% of this data center's electricity use was matched on an hourly basis with carbon-free sources.



An important consideration about low-carbon grids like Finland's is that adding more renewable energy may have a limited impact in reducing the electricity grid's CO_2 emissions. The reason is that the CO_2 emission reductions achieved by wind or solar power in a given hour depends on the carbon intensity of the grid's *marginal generation source* — that is, which type of power plant provides incremental (or "marginal") electricity to the grid when demand increases, and is thus the first to be displaced by zero-fuel-cost renewable generation. Since the marginal generation source in the Nordic countries is often carbon-free hydropower, additional wind power may have the effect of displacing a fellow carbon-free resource. The takeaway is that renewable energy additions are more likely to achieve substantial CO_2 reductions in carbon-intensive regions, in particular where marginal power generation comes from fossil fuels.[10]

Indeed, not every data center region is as carbon lean as Finland. In many regions, the grid mix does contain considerable fossil generation and it's often difficult for us to procure renewable energy due to regulatory barriers or lack of supply.

North Carolina

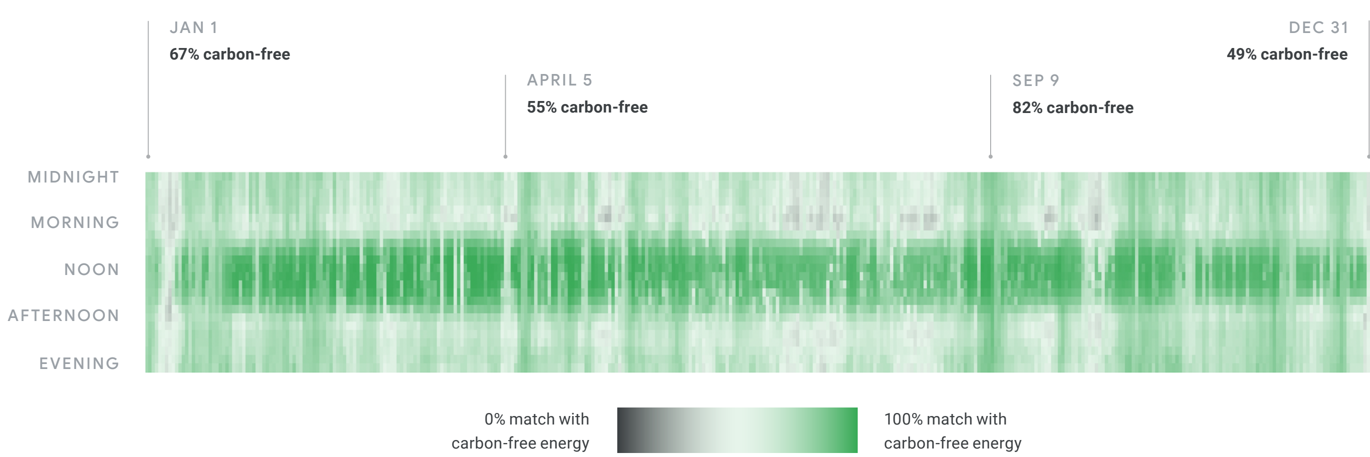
Even in locations where renewables like solar and wind power are available, their variability means they are unable to provide power 24x7. This can be problematic in places where there are few carbon-free sources to step in when sunlight and wind diminish. An example is our data center in Lenoir, North Carolina, where we worked with the local utility to establish one of the first utility solar purchase programs in the country. As a result, daytime energy use at our data center is fairly well matched with carbon-free energy (Figure 7). However, our nighttime energy profile is noticeably more carbon intensive. It's worth noting that the data center's nighttime energy use is still matched with some amount of carbon-free energy, owing to North Carolina's nuclear generation. In 2017, 67% of our North Carolina data center's electricity consumption was matched on an hourly basis with regional carbon-free sources.

FIG. 7

Every hour of electricity use at North Carolina data center

This data center's midday electricity use is matched with regional solar energy, making its carbon-free profile highest during those hours

Overall in 2017, 67% of this data center's electricity use was matched on an hourly basis with carbon-free sources.



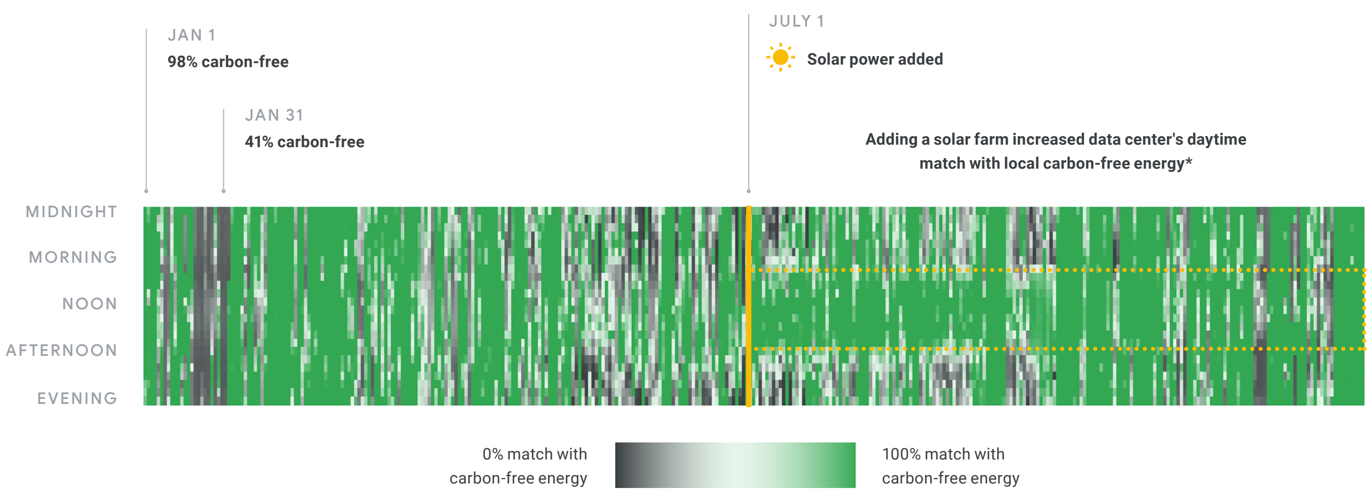
Netherlands

In evaluating our data centers' progress toward 24x7 carbon-free energy use, it's clear that our efforts to add renewables to the grid are bearing major fruit. One example is the Netherlands, where prior to our renewable power purchases in the country, less than 20% of our Eemshaven data center's electricity use coincided with carbon-free energy supply on an hourly basis. But after signing PPAs to add new wind and solar farms, now almost 70% of our data center's electricity consumption is matched hourly with carbon-free sources. Figure 8 shows how our recent procurement of solar power in the Netherlands — which began in July 2017 — has complemented our purchases of wind power to increase our data center's daytime match with carbon-free sources. The CO_2 emissions reductions achieved by these PPAs are significant (in contrast to our Finland example) because the Netherlands' marginal electricity generation source — which solar and wind displace — is primarily fossil fuels.

FIG. 8

Every hour of electricity use at Netherlands data center

Overall in 2017, 69% of this data center's electricity use was matched on an hourly basis with carbon-free sources.



** This heat map assumes that our Netherlands data center's hourly electric load was constant throughout the year (based on January 2017 values). In reality, the data center experienced load growth. We suppress that growth here in order to accentuate the impact that a solar farm can have on carbon-free energy matching. The 69% carbon-free match reported above does reflect the data center's actual load growth.*

Iowa

Another case where our efforts have sizably increased a data center's match with carbon-free energy is in Iowa, where our renewable energy contracts have brought three new wind farms onto the grid. While the region's grid mix in 2017 was just 18% carbon-free, a full 74% of our Council Bluffs data center's energy use was matched on an hourly basis with carbon-free sources, due to our large-scale purchases of wind power.

Although 74% of our Iowa data center's energy use coincided with carbon-free energy over the course of a year, the degree of matching can range significantly across different hours due to the variability of wind. During breezy periods, our Iowa wind farms can produce nearly *three times* as much power as our data center requires — which in our framework counts as a 100% match (Figure 9a).[11] On the other hand, there are days when the wind hardly blows at all; in those cases, the data center is scarcely matched with carbon-free power in any hour and instead has a strongly carbon-based profile (Figure 9b).

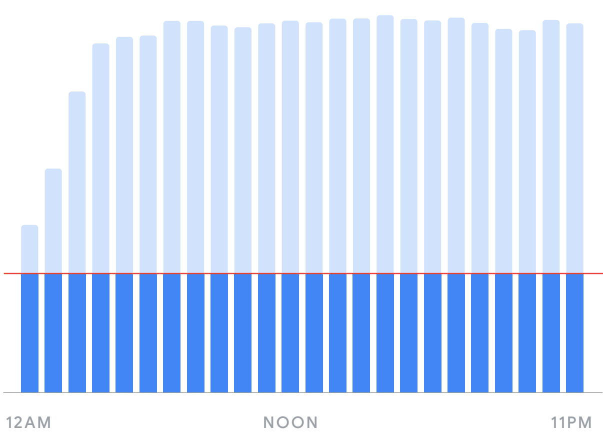


FIG. 9A

High-wind day

A day when Google-contracted wind farms in the Iowa region produced more than enough energy to match data center load in every hour

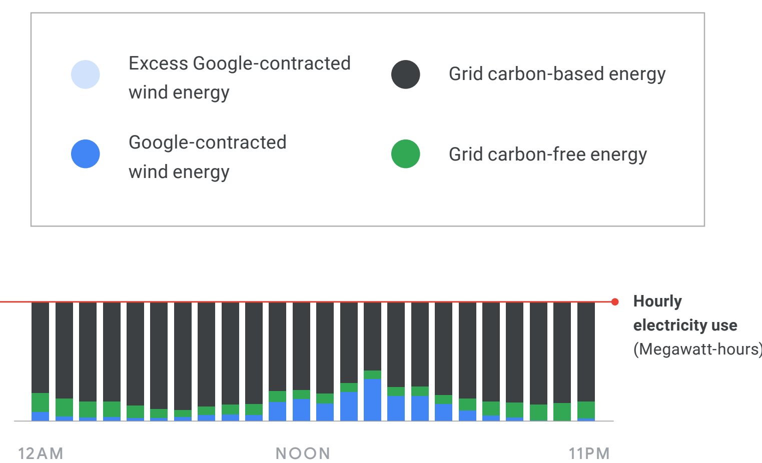


FIG. 9B

Low-wind day

A day when Google-contracted wind farms in the Iowa region did not produce enough energy in any hour to match data center load

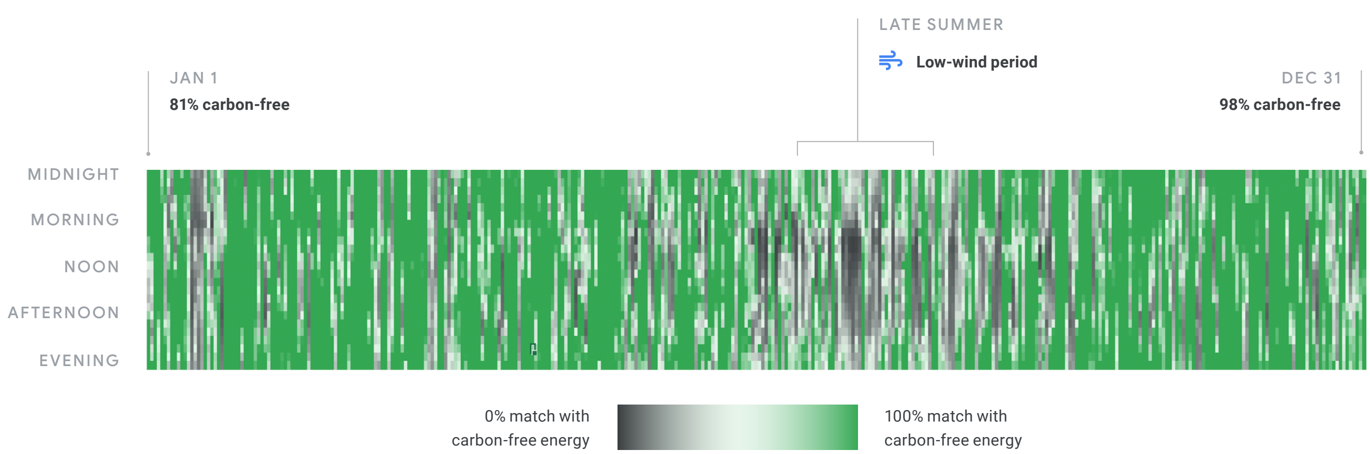
The data above reveals a key insight: heavy development of a single source of variable renewable energy (e.g. multiple wind farms in Iowa) can be effective in increasing a data center's hourly match with carbon-free energy *when* the wind blows, but it is *not sufficient to achieve a 100% match with carbon-free energy in every hour of the year*. Even though in some hours our Iowa wind PPAs produce far more than enough energy to match the local data center's hourly consumption — and on an annual basis produce roughly 20% more than the data center's total annual consumption — the data center is still falling short on 24x7 carbon-free energy. A heat map of our Iowa data center's hourly energy profile (Figure 10) shows that despite many hours of 100% carbon-free energy matching (from windy periods like in Figure 9a), there is also a recurring reliance on carbon-based power (from low-wind times like in Figure 9b).

FIG. 10

Every hour of electricity use at Iowa data center

Although our Iowa data center achieved 100% carbon-free energy during the majority of hours in 2017, there is also a recurring reliance on carbon-based power — most notably in late summer, when wind speeds decline.

Overall in 2017, 74% of this data center's electricity use was matched on an hourly basis with carbon-free sources.



By deploying massive numbers of wind turbines (e.g. that would produce several multiples more electricity than our annual consumption), we might be able to continuously match or exceed data center load with wind generation. But this outsized power capacity would be neither economically practical[12] nor technically advisable. The deployment of cost-effective, large-scale energy storage could conceivably help create better matching of renewable energy supply with data center electric demand, particularly over the course of a day. However, storage may not necessarily be able to overcome major seasonal variations in renewable supply (e.g. it's currently impractical to store summertime solar energy for use in wintertime). To attain a 24x7, 100% match with carbon-free energy, it will be necessary to create a diverse portfolio of technologies in each region that collectively provide a steady stream of carbon-free electricity around the clock.

Taiwan

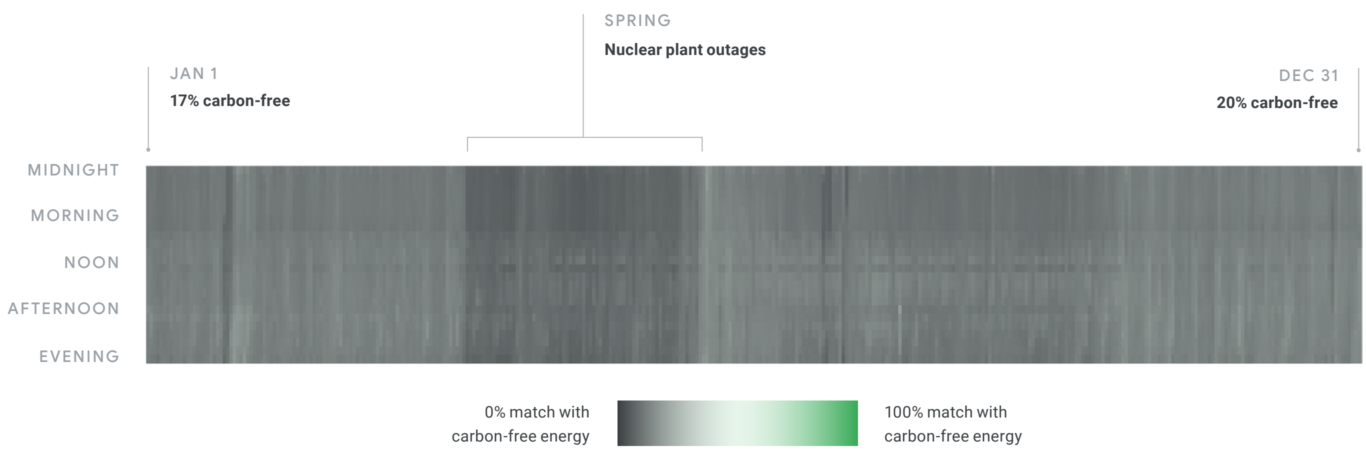
While many of our data center campuses have made noteworthy progress toward hourly matching of electricity consumption with carbon-free electricity, there remain other campuses that have opportunities to improve. One example is our data center in Changhua County, Taiwan. Although the grid mix has some amount of carbon-free sources like nuclear, solar, and wind, it is still dominated by coal and natural gas. Evident in the heat map below, less than 20% of our Taiwan data center's electricity consumption in 2017 was matched on an hourly basis with regional carbon-free sources.

FIG. 11

Every hour of electricity use at Taiwan data center

Hourly carbon-free matching fell to as low as 8% in spring, due to outages at nuclear power plants

Overall in 2017, 16% of this data center's electricity use was matched on an hourly basis with carbon-free sources.



To boost the carbon-free profile of our operations in Changhua County, we are actively working to source carbon-free electricity for our data center.

After careful consideration and at the urging of Google and others, in January 2017 the Taiwanese legislature amended the country's Electricity Act to open up the energy market, thereby enabling companies to directly purchase renewable energy. We are hopeful that this change will lead to new carbon-free power sources in Taiwan and be replicated elsewhere in Asia.

III. Insights Along the Path to 24x7 Carbon-Free Energy

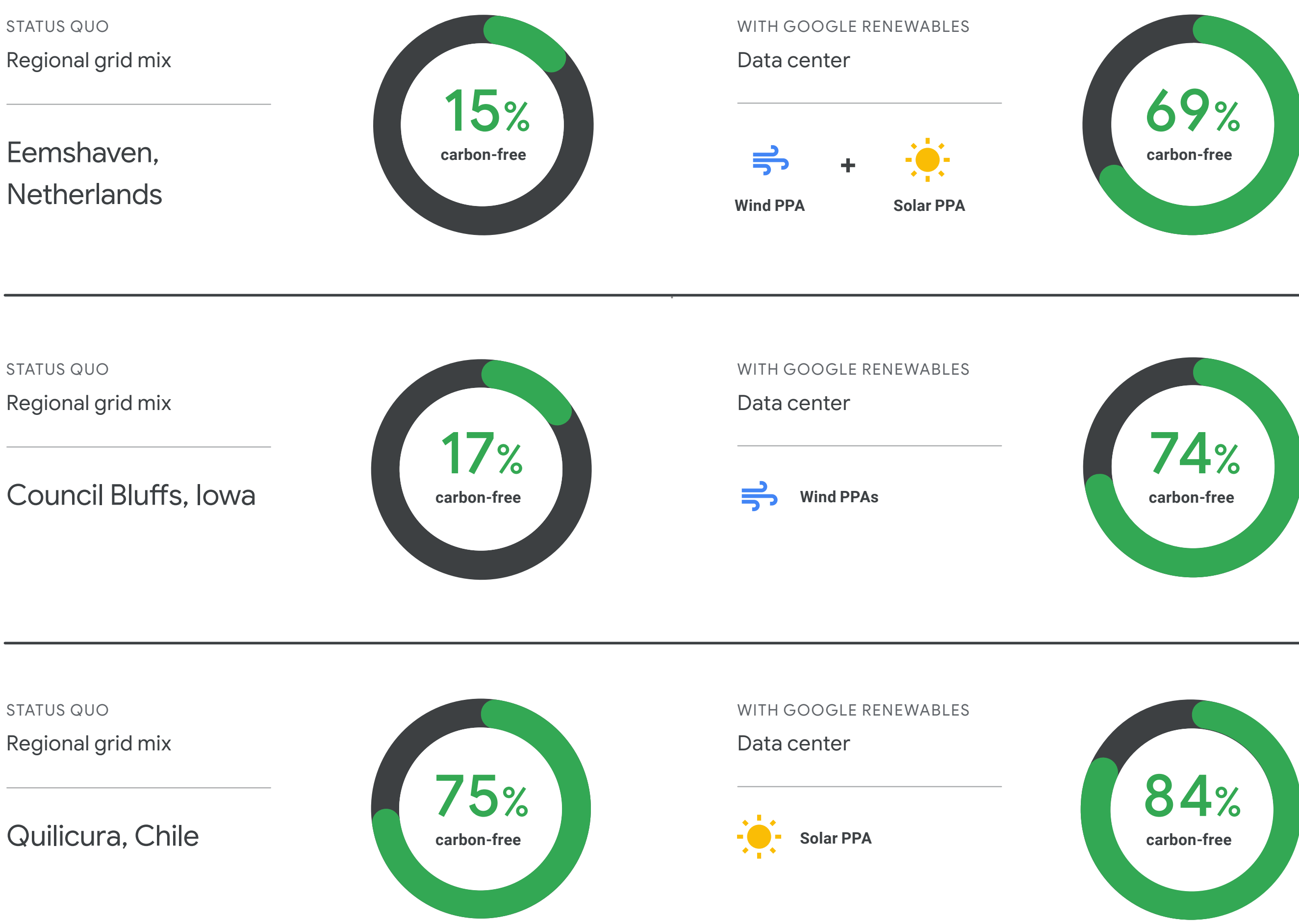
In conducting our first examination of how Google data centers measure up against achieving 24x7 carbon-free energy, we've developed a handful of insights that can guide us as we move forward.

1. **Our renewable energy purchasing efforts (to match 100% of our annual electricity use) have enabled us to make meaningful progress toward 24x7 carbon-free energy.** By adding more than 25 wind and solar projects — totaling over 3 gigawatts of new generation capacity — across various data center regions since 2010, we have greatly increased the level of hourly matching between our data center load and regional carbon-free energy supply. Figure 12 highlights examples of this around the world. In all data center regions where we have signed renewable PPAs, at least 65% of our data center's electricity consumption in 2017 was matched on an hourly basis with carbon-free energy.

2. **A diverse portfolio of carbon-free energy sources — whether variable or dispatchable — can have a greater impact than a single variable source.** In the absence of long-duration energy storage, a single source of renewable energy is generally not sufficient to provide a 24x7, 100% match with a data center's load. Even in a region where our wind PPAs can produce up to three times as much power as our data center requires, there are also breezeless hours or days when our load is matched with scarcely any carbon-free power. Through the lens of 24x7 carbon-free energy, adding more of a single variable resource yields diminishing returns. For the foreseeable future, we anticipate having the most success with a geographically and technologically diverse portfolio that consists of different types of variable renewables (e.g. solar, wind), firm carbon-free sources (e.g. nuclear, geothermal, biomass), and next-generation solutions (e.g. low-cost energy storage, carbon capture and storage, and flexible electricity demand that is optimized to coincide with the availability of low-carbon energy sources).

FIG. 12

Examples of Google renewable PPAs enabling progress toward 24x7 carbon-free energy



3. **Existing nuclear and hydropower are delivering significant amounts of carbon-free electricity to the grid in some data center regions.** Data centers that perform well on the metric of 24x7 carbon-free energy are often located in regions that have a substantial amount of carbon-free energy already on the grid. In Finland, for instance, nuclear and hydropower account for more than 40% of the country's overall grid mix. Accordingly, it's important for governments, utilities, and other energy market players to carefully consider retirement of existing firm carbon-free generation.

Ultimately, we envision and desire grid mixes worldwide to be 100% carbon free, which will likely entail an important role for both renewable energy and firm carbon-free generation that can scale cost-effectively.

4. **In regions where the grid is carbon intensive and we currently have no PPAs, signing a renewable energy PPA would immediately improve our carbon-free energy performance.** In regions like Asia and the Southeastern US, the barriers to renewable energy development so far have not been technology or price, but rather policy and market structure. This suggests a critical need to evolve utility regulation and energy business models at the state and regional levels. As retail and wholesale energy markets become more nimble and customer-centric, such that any electricity customer who wants clean power can purchase it, we will be better positioned to deploy carbon-free energy worldwide.

5. **Maximizing the climate benefit of carbon-free energy requires analysis of marginal electricity generation**. The emissions impact of additional carbon-free energy generation depends on the resource mix of the region where that generation is added. When deciding where in the world to add more carbon-free energy, it is important to evaluate the effect that new energy supply will have on making the local grid more carbon free. In general, power supplied by a new solar or wind farm can reduce a region's CO_2 emissions, in that it provides a clean substitute for incremental (or "marginal") generation from existing carbon-based power plants. However, in some regions, adding new carbon-free energy may have a limited effect in reducing CO_2 emissions if the region's marginal electricity generation already comes from carbon-free sources such as hydropower. The carbon profile of marginal electricity generation is an area of ongoing research — and one that can help us maximize the climate benefit of our energy initiatives.

The Path Forward

The scientific evidence is clear: tackling climate change is an urgent global imperative and will require full-scale decarbonization of the world's energy systems. And that is our vision: a world that runs exclusively on carbon-free energy — 24 hours a day, 7 days a week, 365 days a year.

Google is committed to doing its part to speed the transition to a 24x7 carbon-free energy future. We have been carbon neutral since 2007, and in 2017 we met our goal to match 100% of our global energy consumption with renewable energy purchases. We are now the largest non-utility buyer of renewable energy in the world. As this paper demonstrates, our purchases of renewable energy have helped us make important progress towards 24x7 carbon-free energy; in every region where Google has signed a renewable energy PPA, our data centers are at least 65% matched on an hourly basis with carbon-free energy. Renewable energy will play an important role in decarbonizing the energy system, and we will continue to procure diverse types of renewables — in a greater number of regions — as we grow.

Meeting our 100% renewable energy purchasing goal is a major milestone for us, and we are excited to see the many other companies that have made similar commitments. But we are still in the early stages of completing the journey to 24x7 carbon-free energy. That is the real prize, and all governments, companies, and organizations should not lose sight of that aspiration.

Achieving 24x7 carbon-free energy will be no easy feat. It will require innovations across policy, technology, and business models.

We'll need policy and market reforms that break down barriers to carbon-free energy procurement, as well as new policies that recognize the societal importance of carbon-free energy and appropriately price the attributes of different power sources. Google will continue to promote electricity market reforms that unlock access to carbon-free power around the world.

We'll also need vigorous development and deployment of emerging technologies — such as energy storage, advanced nuclear, and carbon capture and storage — that boost the availability of carbon-free energy around the clock. Google is positioned to apply its expertise in resource efficiency and problem-solving strategies like machine learning to help advance the energy technology frontier.

Finally, we'll need new energy contracting approaches that focus on providing firm low-carbon electricity 24x7, likely through a combination of multiple generation sources or the adoption of energy storage. We look forward to partnering with innovators across the energy marketplace to make these next-generation commercial constructs a reality.

As we aim our sights toward 24x7 carbon-free energy, we know we have our work cut out for us and couldn't be more excited to push forward.

Acknowledgments

Special thanks to WattTime for their partnership and rigor in helping evaluate our data centers' carbon-free energy profiles.

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The views expressed in this paper, as well as any errors, are Google's own.

Notes

1. Total annual electricity consumption in Rhode Island is around 7.5 billion kWh. Rhode Island is America's 43rd most populous state — home to more than a million people and 94,000 businesses.

2. To ensure that Google is the driver for bringing new clean energy onto the grid, we insist that all projects be "additional." This means that we seek to purchase energy from not yet constructed generation facilities that will be built above and beyond what's required by existing energy regulations.

3. For more than a decade, we've worked to make Google data centers some of the most efficient in the world. Compared with five years ago, we now deliver more than 3.5 times as much computing power with the same amount of electrical power. For details, see our 2018 Environment Report.

4. We provisionally count biomass energy as carbon free because, although it emits biogenic CO_2 in electricity generation, it can in some circumstances be net carbon free. In recent years, scientists have raised meaningful concerns about greenhouse gas emissions associated with both biomass and hydropower. We categorize them as carbon free in our current framework because, if managed responsibly, their impact can be minimized. We continue to monitor developments around their environmental, social, and greenhouse gas profiles. Our intent is to encourage sustainable and truly carbon-free initiatives and to characterize them properly in our framework.

5. Our framework's definition of "regional grid" corresponds to the area over which power system demand and supply are finely balanced by a regional grid operator (e.g. a balancing authority). For further detail, see Technical Appendix.

6. Carbon-free energy from a Google PPA site is generated in the same grid operating region as a given data center but does not have an exclusive direct connection to the data center. After being generated, the electricity is indistinguishably mixed into the general supply of electricity that is delivered to all power customers in the region, including Google's data center.

7. In calculating a data center's hourly match with regional carbon-free energy, we first count Google's renewable PPAs. We do this because we have a contractual right to that electricity production and its environmental attributes, and our PPAs have directly led to the addition of that carbon-free energy to the grid (see our discussion of "additionality").

8. All renewable energy that we contract through our PPAs is delivered to the regional electricity grid, including the renewable energy production that exceeds our consumption in any given hour. Although the physical electricity may be consumed by someone else on the grid, we retain and retire the renewable energy attributes (e.g. renewable energy certificates [RECs] or Guarantees of Origin [GoOs]), which represent the "greenness" of the electricity and give us the unique right to claim it as part of our sustainability efforts.

9. In 2017, most of Google's renewable power generation in the Nordic region was located in Sweden, rather than in Finland itself. While they technically operate separate grids, Finland and Sweden are part of a shared competitive electricity market (Nord Pool), and Finland directly imports a large amount of electricity from Sweden. We thus categorize our hourly wind generation in Sweden as "matched" with our electricity consumption in Finland.

10. We've partnered with the emissions analysis non-profit WattTime to begin characterizing the carbon intensity of marginal electricity generation in our data center regions. We continue to study the impact that our renewable PPAs have on reducing CO_2 emissions — via their displacement of the grid's marginal generation sources — so that over time we can maximize the climate benefit of our energy procurement.

11. While the excess wind energy (>100% of our data center load) produced on windy days in Iowa cannot increase the data center's hourly carbon-free energy match above 100%, it does reduce CO_2 emissions of the electricity grid when it displaces carbon-based marginal generation (e.g. from natural gas).

12. See Platt, Pritchard, & Bryant, 2017 and Google Research's interactive cost-of-electricity explorer.

N.B. *This version of our paper reflects minor grammatical, typographical, and formatting updates made in November 2018. We also lightly modified the color scheme of the Carbon Heat Maps, resulting in a slightly difference appearance relative to the original October 2018 version of the paper.*

Technical Appendix

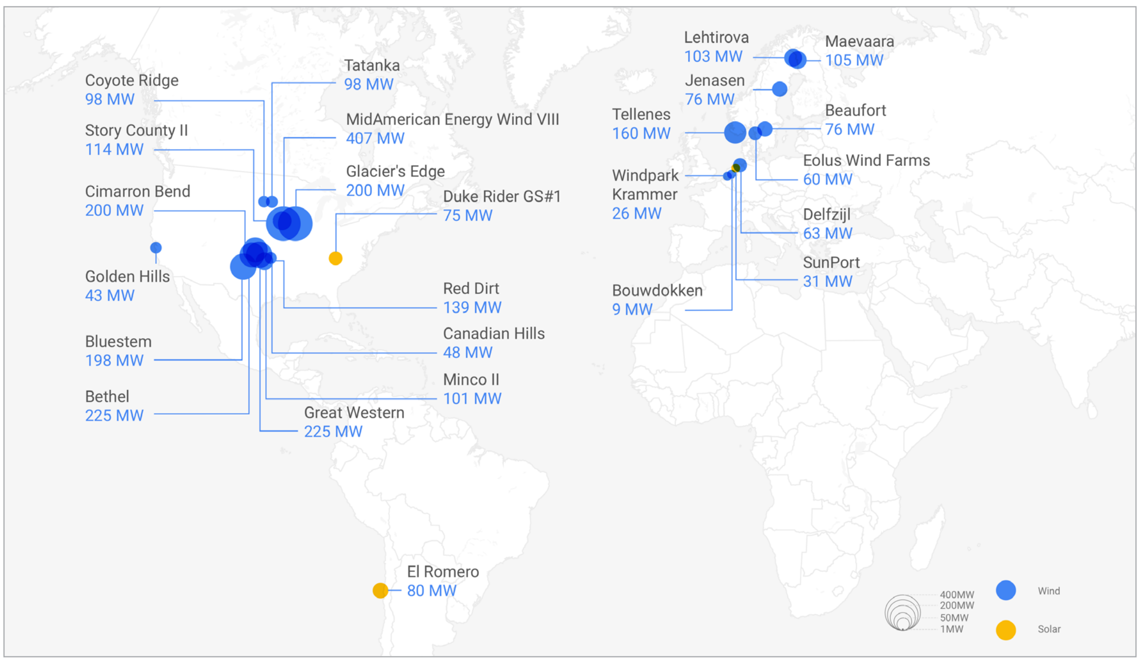
For each grid region where Google has data centers, the data center's load was first compared to available contracted carbon-free energy from Google PPAs. This comparison was used to identify hourly gaps of overproduction or underproduction of carbon-free-energy. If more energy was consumed by the data center than generated by contracted carbon-free energy in a given hour, the remaining demand was apportioned to grid mix — using the appropriate carbon-free versus carbon-based ratio for that grid region. For regions where Google does not have any renewable energy assets, the same approach was used, but without the initial contribution from contracted carbon-free energy.

Electricity consumption data: Data center electricity load is relatively constant over the course of a given month. Therefore, we have computed hourly load as a constant average value based on total electricity consumption in the corresponding calendar month, as reported on monthly utility invoices for each data center. The map below shows our global data center fleet as of 2017.

Google's data center fleet as of 2017

Electricity production data from Google PPA sites: The energy generation from Google's contracted renewable projects was determined using metered data acquired from the respective project developer. The PPAs considered are shown in the map below.

Google's Renewable Energy PPAs as of 2017



A note about regional grid mix and Google PPAs: In all regions, Google's renewable energy purchases are less than 1% of regional grid electricity supply and are typically substantially less than that. As a result, our PPAs currently have a de minimis effect on the broader grid mix. As Google's contracted carbon-free energy grows and becomes a larger share of the mix, we can account for this by removing our PPA generation from overall grid mix data.

A regional grid mix encompasses all generating resources in a given region, including resources that might be under contract by others' PPAs. To assess the CO_2 emissions profile of Google's data center locations, the entire grid mix is important to consider.

Regional boundaries for analysis: Our framework's definition of "regional grid" corresponds to the area over which power system demand and supply are finely balanced by a regional grid operator (e.g. a balancing authority). These regions are listed below in the Regional Grid Operator column.

APPENDIX TABLE 1

Grid regions and data sources

COUNTRY / AREA	DATA CENTER LOCATION	REGIONAL GRID OPERATOR	DATA SOURCES
United States	Berkeley County, South Carolina	South Carolina Public Service Authority (SC)	Net generation: EIA electric system operating data
	Council Bluffs, Iowa	Midcontinent Independent Transmission System Operator, Inc. (MISO)	
	Douglas County, Georgia	Southern Company Services, Inc. - Trans (SOCO)	
	Lenoir, North Carolina	Duke Energy Carolinas (DUK)	
	Mayes County, Oklahoma	Southwest Power Pool (SPP)	
	The Dalles, Oregon	Bonneville Power Administration (BPA)	
European Union	Dublin, Ireland	EirGrid	Actual generation mix: ENTSO-E transparency platform
	Eemshaven, Netherlands	Tennet	
	Hamina, Finland	Fingrid and other Nord Pool grid operators	
	St Ghislain, Belgium	Elia	

COUNTRY OR AREA	DATA CENTER LOCATION	REGIONAL GRID OPERATOR	DATA SOURCES
Singapore	**Singapore**	Energy Market Authority of Singapore	**Monthly generation mix: energy market authority**
Chile	**Quilicura, Chile**	Sistema Interconectado Central (SIC)	**Electricity generation mix: national energy commission**
Taiwan	**Changhua County, Taiwan**	Taiwan Power Company	**Electricity generation mix data**