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Impact of energy efficiency on reducing consumption in data centers with power purchase agreements - PPAs

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***Abstract*—This research analyzes the impact of energy efficiency on reducing data center electricity consumption through Power Purchase Agreements (PPAs), using Google as a case study. A mixed-method approach, combining qualitative and quantitative analysis, was applied to assess the strategic implementation of energy efficiency measures and their measurable effects on operational performance. The study relied on historical data, technical reports, and key energy efficiency metrics to evaluate Google's integration of PPAs and their role in minimizing electricity consumption and carbon footprint. Power Usage Effectiveness (PUE) served as the primary metric to assess efficiency, with a detailed regional and temporal analysis revealing significant performance variations. The findings indicate that European data centers, such as those in Eemshaven (Netherlands) and Dublin (Ireland), consistently achieved lower PUE values, benefiting from favorable climate conditions and advanced energy management. In contrast, North American locations exhibited a broader range of efficiency levels, while Asian facilities, particularly in Singapore, faced greater cooling challenges due to warm climates. Additionally, the study highlights the effectiveness of AI-driven workload distribution, real-time monitoring, and advanced cooling technologies in optimizing energy consumption. The results demonstrate that the integration of PPAs with energy efficiency initiatives not only ensures a stable supply of renewable energy but also enhances operational sustainability and contributes to grid decarbonization. This research underscores the importance of continuous innovation in data center energy management, offering insights applicable to the broader industry.**

Keywords: Energy, efficiency, data, centers, PPA.

I. INTRODUCTION

The exponential growth in data processing demand has led to a significant increase in energy consumption in data centers. It is estimated that these facilities account for approximately 1% of global electricity consumption, a figure that continues to rise due to the expansion of digital services, cloud computing, and artificial intelligence [1]. In response to this challenge, energy efficiency has become a strategic priority for technology companies, driving the development of innovative solutions such as the use of artificial intelligence to optimize energy consumption and the implementation of renewable energy power purchase agreements (PPAs) [2].

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A notable case is Google, which has successfully reduced its data center cooling energy consumption by 40% through the implementation of DeepMind's artificial intelligence technology [3]. Similarly, companies like Amazon Web Services have adopted advanced free cooling and liquid cooling technologies to decrease energy demand across their infrastructures [4]. These strategies not only lead to a substantial reduction in environmental impact but also enhance operational stability and reduce long-term costs [5].

PPAs have emerged as a key solution to ensure a long-term supply of renewable energy for data centers. Leading companies have signed supply contracts with solar and wind farms to cover 100% of their energy consumption with renewable sources [6]. These agreements enable technology firms to stabilize electricity costs and reduce their carbon footprint, aligning with increasingly stringent environmental regulations [7]. The integration of renewable energy into data center operations not only enhances sustainability but also contributes to the resilience of the global energy system [8].

Recent research has demonstrated that the application of advanced thermal management techniques and automation in data center infrastructure can result in significant improvements in energy efficiency [9]. Furthermore, the development of AI-based predictive models has enabled the optimization of workload distribution, thereby minimizing energy waste during periods of low demand [10]. With these advancements, the data center sector continues to evolve toward a more efficient and sustainable model, supported by technological innovations and a commitment to clean energy adoption [11].

This paper is organized as follows: Section II presents the theoretical framework, which includes power purchase agreements (PPAs) in data centers, energy efficiency measures in data centers, and the relationship between PPAs and energy efficiency. Section III describes the methodology, which is based on a case study focused on Google and aims to evaluate the impact of energy efficiency on reducing data center consumption through power purchase agreements (PPAs). Section IV discusses Google's energy efficiency strategies and other implemented actions. Section V presents the research results and Finally, Section VI presents the conclusions.

II. Theoretical framework

A. Power Purchase Agreements (PPAs) in Data Centers

Power purchase agreements (PPAs) are long-term contracts between an energy provider and a consumer, establishing the purchase of electricity generated from renewable sources at a predetermined price. These agreements enable data centers to secure a stable supply of clean energy, reducing their carbon footprint and mitigating the volatility of electricity prices in the market [12]. In addition to providing financial stability for companies, PPAs foster investment in renewable energy infrastructure, promoting the transition toward a more sustainable electricity grid. There are two main types of PPAs: physical and virtual. Physical PPAs involve the direct delivery of electricity from a renewable energy generator to the consumer through the electrical grid, thereby ensuring energy supply to the data center infrastructure. Figure 1 illustrates the flowchart of the electricity supply process to a data center through a physical Power Purchase Agreement (PPA) with a renewable energy source (wind or solar).

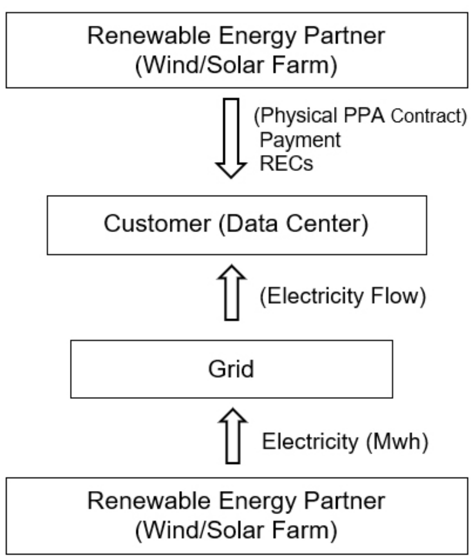

Fig. 1. Flowchart of a physical PPA in a data center

Where:

- **Renewable energy partner (Wind/Solar farm):** Represents the renewable energy provider (a wind or solar power plant). A physical PPA contract is established, which includes payment for the supplied electricity and renewable energy certificates (RECs) that certify the use of renewable energy.
- **Customer (Data center):** The final consumer of electricity (the data center), which receives the physical flow of electricity generated by the renewable power plant.
- **Grid (Electric grid):** Acts as an intermediary in the electricity supply process. The electricity flows from the renewable power plant to the grid, and the data center subsequently receives electricity from the grid.

In Power purchase agreements (PPAs), distinguishing between physical and virtual types is crucial. "The upper section of the flowchart illustrates the PPA contract between the renewable energy provider and the data center (including payment and RECs). The lower section represents how electricity is transmitted through the grid before reaching the consumer" [13]. These agreements involve significant financial risks due to their long-term commitments [14]. "In contrast, virtual PPAs also known as financial or synthetic contracts—do not entail the physical delivery of electricity. Instead, they function as financial agreements" [15]. These structures impact business energy efficiency and can be evaluated using "advanced evaluation methods based on entropy and independence" in multi-energy systems [16]- [17].

B. Relationship between PPAs and Energy Efficiency

The expanding data processing demand has increased data center energy consumption. Energy efficiency measures combined with Power Purchase Agreements (PPAs) now form a key sustainability strategy. PPAs enable renewable electricity sourcing while ensuring cost stability and reducing emissions. PPAs' sustainability impact increases when paired with efficiency strategies. Hardware optimization, advanced cooling, and AI-managed consumption maximize PPA effectiveness by reducing total energy requirements [18]. AI-driven workload management dynamically adjusts demand based on renewable energy availability. Data centers can modulate consumption according to grid renewable availability. AI technologies predict renewable production, adjusting workloads to utilize peak generation periods [19]. Advanced PPA management models provide greater energy supply flexibility [20]. Google and Amazon have optimized PPAs through machine learning integration. Cooling advancements like liquid and free cooling significantly reduce energy consumption, decreasing renewable energy contract volumes [21], lowering operational costs and improving clean energy contract profitability. PPAs ensure renewable energy access while amplifying impact when combined with efficiency strategies. This integration optimizes consumption and supply, reducing the environmental footprint of this rapidly growing industry [22].

III. Methodology

The methodology employed in this research is based on a case study focused on Google, aiming to evaluate the impact of energy efficiency on reducing data center consumption through Power Purchase Agreements (PPAs). To achieve this, a mixed-method approach combining qualitative and quantitative analysis is utilized, allowing for an in-depth examination of both the implemented strategies and their measurable effects on energy performance. The study relies on historical data, technical reports, and energy efficiency metrics provided by Google and other relevant sources. A detailed analysis of PPA integration within Google's energy strategy is conducted, considering its impact on both energy consumption reduction and carbon footprint mitigation. To assess data center efficiency, the Power Usage Effectiveness (PUE) metric is employed, which measures the ratio of total facility energy consumption to the energy consumed exclusively by IT equipment. The analysis involves the collection and comparison of PUE values from Google's data centers over different time periods, benchmarking them against industry standards to determine the extent of the efficiency improvements achieved. Additionally, various optimization measures implemented by the company are examined, including advanced energy management strategies, the deployment of more efficient cooling systems, and the use of real-time monitoring tools to identify and rectify operational inefficiencies. Finally, Google's electricity consumption data is compared with broader industry trends in the data center sector, enabling validation of the effectiveness of its strategies and confirming its contribution to enhanced energy efficiency and carbon emission reduction through the use of PPAs and other optimization technologies.

IV. Google Case

Google offers a significant advantage in terms of its scale and data accessibility, as it regularly publishes sustainability and energy consumption reports that facilitate analysis using both historical and real-time data through standardized metrics such as PUE [23]. This transparency, combined with the availability of detailed information and regional monitoring of its data centers, enables rigorous comparisons and a precise evaluation of the effectiveness of energy efficiency strategies implemented through PPAs.

A. *Google's Energy Efficiency Strategies*

Google has established itself as a leader in data center energy efficiency by implementing innovative strategies that reduce environmental impact while maintaining high computational performance. As one of the largest global technology companies, Google operates an extensive network of data centers that consume significant amounts of electricity. To mitigate this, the company has prioritized efficiency improvements and the adoption of renewable energy sources through Power Purchase Agreements (PPAs). Google's commitment to carbon neutrality and energy efficiency aligns with its broader sustainability goals. By investing in cutting-edge technologies and AI-driven optimization, the company continuously refines its energy usage patterns. These advancements have not only reduced operational costs but also strengthened the reliability and sustainability of its infrastructure [24]- [25].

B. *Integration of PPAs in Google's Energy Strategy*

Google pioneers Power Purchase Agreements (PPAs) to secure renewable energy for data centers, establishing long-term contracts with wind and solar providers. These agreements reduce fossil fuel dependence while expanding clean energy infrastructure, allowing Google to match 100% of its global electricity use with renewable purchases by 2021. Through PPAs, Google acquires renewable electricity from projects on the same power grids as its data centers. While this energy can't always be physically delivered to facilities, purchases help decarbonize local grids. Google sells the electricity at wholesale prices and retains renewable energy certificates (RECs), preventing others from claiming the environmental benefits and allowing Google to count its electricity as carbon-free. This approach reduces environmental impact while driving renewable energy investment. Figure 2 shows the general framework for renewable energy procurement through power purchase agreements (PPAs) [26].

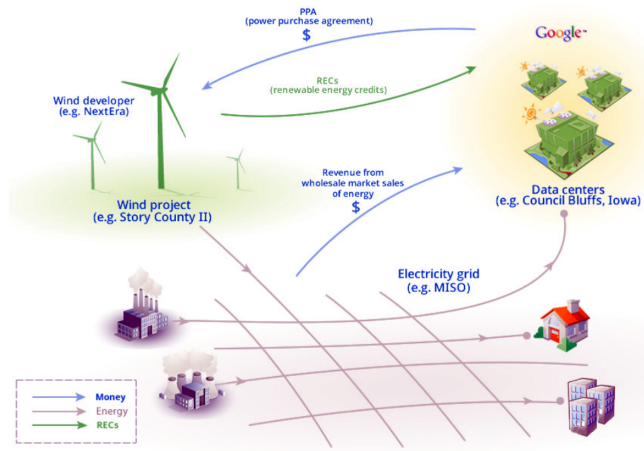

Fig. 2. Google's renewable energy procurement framework with PPAs

Additionally, Google employs load shifting techniques, ensuring that energy-intensive operations are scheduled during periods of peak renewable generation. This strategy enhances grid reliability while further integrating clean energy sources into daily operations [27].

C. *Data Center Efficiency*

Google invests in efficient data centers to optimize performance while reducing energy use through cutting-edge infrastructure that minimizes waste and enhances resilience. Their approach combines server consolidation and virtualization to maximize computing with fewer machines, along with custom-built hardware featuring energy-efficient processors that have increased computing performance per watt by 30% over five years. Additionally, they implement intelligent power distribution using machine learning to schedule intensive processes during peak renewable energy availability, reducing peak power demand by 25% reduction in peak power demand across its facilities [28]- [29]. Google's calculations encompass data from all its global data centers, not solely the most advanced or recently built facilities. Moreover, measurements are conducted year-round rather than being limited to colder seasons. Additionally, all overhead energy sources are incorporated into its efficiency metrics. Figure 3 illustrates the PUE measurement boundaries within Google's data centers [30].

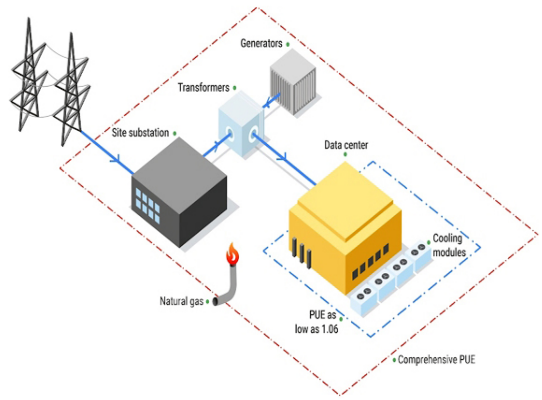

Fig. 3. PUE measurement limits in Google's data centers

D. Google's Methodology for Measuring and Optimizing Energy Efficiency

The subsequent analysis examines Google's comprehensive methodological framework for energy efficiency measurement and optimization within its global operational infrastructure. This systematic approach represents a significant contribution to sustainable technological practices in large-scale computing environments. Through this multifaceted methodology, Google has established industry-leading standards for energy efficiency while simultaneously advancing corporate sustainability objectives. The five steps of the methodology are the following:

1) **Methodological basis**: Google has established a comprehensive methodological framework for energy efficiency assessment across its operational infrastructure. This framework adheres to internationally recognized standards while incorporating rigorous scientific methodologies for energy management. The approach integrates lifecycle analysis methodologies, comparative benchmark assessments, and statistical predictive modeling derived from historical consumption patterns. The Table I shows the main elements of methodological basis.

TABLE I
METHODOLOGICAL BASIS

Element	Description
Standard Name	Power Usage Effectiveness (PUE)
Organization	The Green Grid
Formula	PUE = Total data center energy / Energy used by IT equipment
Purpose	Measures how much energy is actually used for computing vs. support systems

2) **Technologies and tools used**: The implementation necessitates deployment of advanced technological infrastructure, primarily comprising real-time monitoring systems utilizing extensive networks of IoT sensor arrays. These systems facilitate continuous measurement of critical environmental and operational parameters. The corporation has developed proprietary analytical platforms which centralize heterogeneous data streams and apply machine learning algorithms for predictive modeling. The Table II shows the main elements of technologies and tools used.

TABLE II
TECHNOLOGIES AND TOOLS USED

Technology / System	Main Function
IoT Sensors	Real-time measurement of energy, temperature, humidity, airflow
SCADA	Supervisory control and data acquisition for industrial systems
BigQuery / GFS	Storage and analysis of large-scale energy data
Dashboards (Grafana)	Real-time data visualization for operational staff
DeepMind AI	Intelligent optimization of cooling and energy systems

3) **Data logging sequence**: The data acquisition protocol follows a structured sequential methodology designed to maximize data integrity. Initial collection occurs at predetermined intervals, followed by automated validation procedures that identify anomalous values. The methodology incorporates a sophisticated metadata framework that correlates energy consumption metrics with specific operational events, enabling causal analysis of consumption variations. The Table III shows the main elements of Data logging sequence.

TABLE III
DATA LOGGING SEQUENCE

Step	Description
1	Instrumentation: Installation of sensors at key energy and environmental points
2	Real-Time Data Capture: Continuous data collection via SCADA and sensor networks
3	Transmission & Verification: Data sent to central systems with automatic validation
4	PUE Calculation: Separate readings for IT vs. total energy to compute accurate PUE
5	AI Analysis: DeepMind predicts optimal conditions and adjusts system settings
6	Visualization & Control: Dashboards provide real-time metrics to engineers
7	Storage & Audit Trail: Digital logs stored in distributed databases for review and compliance
8	Aggregated Reporting: Quarterly and annual summaries published publicly

4) **Internal methodological approach**: The internal framework adheres to a cyclical continuous improvement paradigm comprising interrelated procedural phases. The process initiates with comprehensive energy consumption audits that identify optimization opportunities through statistical analysis. Prior to full-scale implementation, proposed solutions undergo controlled experimental valida-

tion. The methodology incorporates a rotational prioritization framework whereby different system components receive focused optimization attention sequentially. The Table IV shows the main elements of internal methodological approach.

TABLE IV
INTERNAL METHODOLOGICAL APPROACH

Descriptive Term	Application at Google
PUE-Based Framework	Based on the international energy efficiency standard
Real-Time Energy Monitoring	Real-time tracking and analytics
AI-Enhanced Infrastructure Optimization	AI-driven adjustments to improve energy use
Data-Driven Operational Control	All decisions and automation based on real-time data and analytics

5) **Key outcomes**: This methodological framework has yielded quantifiable improvements across multiple assessment metrics. The organization has achieved a Power Usage Effectiveness ratio of 1.1, representing a significant 35% improvement compared to the industry median of 1.7. Financial analysis indicates substantial cost avoidance, with annual expenditure reductions estimated at hundreds of millions of dollars. The Table V shows the main elements of key outcomes.

TABLE V
KEY OUTCOMES

Metric	Value / Result
Google's Average PUE (2023)	1.10
Cooling Energy Savings via AI	40% reduction in cooling energy usage
Data Transparency	Results publicly shared on Google's Sustainability portal

E. Data Center PUE Performance

Power Usage Effectiveness (PUE) measures data center energy efficiency. Google achieves industry-leading low PUE ratings of around 1.1 (versus industry averages of 1.5-2.0) through advanced cooling and power distribution technologies. Google implements direct-to-chip liquid cooling, immersion cooling, and free cooling systems that reduce traditional air conditioning needs, cutting cooling-related energy use by 50%. By combining low PUE with renewable energy sources through PPAs, Google saves an estimated 2.5 TWh of electricity annually, equivalent to powering over 2 million U.S. homes [31]. The company uses multiple power meters throughout its data centers to monitor energy consumption of both cooling infrastructure and IT equipment, enabling precise PUE calculations that account for all energy-consuming components.

Figure 4 shows the IT equipment and general expense elements.

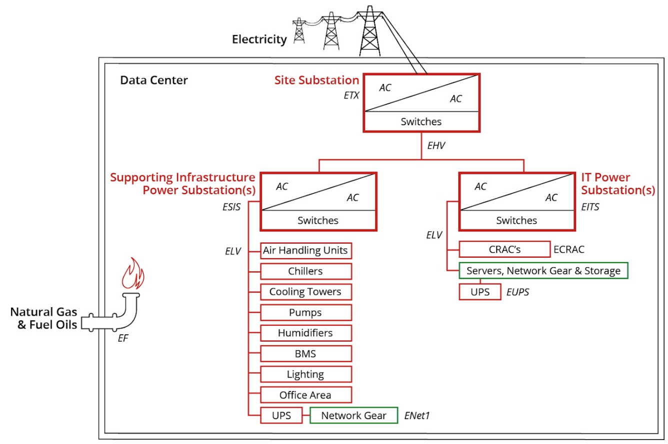

Fig. 4. IT equipment and general expense elements

$$\text{PUE} = \frac{\text{ESIS} + \text{EITS} + \text{ETX} + \text{EHV} + \text{ELV} + \text{EF}}{\text{EITS} - \text{ECRAC} - \text{EUPS} - \text{ELV} + \text{ENet1}}$$

Where:

- **Red**: General expense energy
- **Green**: IT energy
- **ESIS**: Energy consumption to allow infrastructure power substations to supply the cooling plant, lighting, office space, and some network equipment.
- **EITS**: Energy consumption for IT power substations supplying servers, network, storage, and computer room air conditioning (CRAC) equipment.
- **ETX**: Medium- and high-voltage transformer losses.
- **EHV**: High-voltage cable losses.
- **ELV**: Low-voltage cable losses.
- **EF**: Energy consumption of fuels in the facilities, such as natural gas and gasoline.
- **ECRAC**: Energy consumption of CRAC units.
- **EUPS**: Energy loss from uninterruptible power supply (UPS) systems that provide electricity to servers, network, and storage equipment.
- **ENet1**: Energy of the network room.

When evaluating the power consumption of IT equipment, only servers, storage systems, and networking devices are included in the assessment. Other components are categorized as overhead. For instance, electrical losses from a server's power cable are considered overhead rather than IT power. Similarly, the total electricity supply from the utility grid is measured at the substation level, with transformer losses at the substation incorporated into the PUE calculations.

To measure energy consumption over time, Google utilizes multiple power meters across its data centers. It monitors the energy usage of both cooling infrastructure and IT equipment through individual meters, enabling highly precise PUE calculations. These PUE values account for all energy-consuming components. To achieve this, Google employs dozens or even hundreds of energy meters within its facilities. The Table

VI shows the annual PUE for the last four years at Google campuses that had at least 12 months of available data.

TABLE VI
PUE REPORT FOR GOOGLE'S CAMPUSES

Campuses	2024	2023	2022	2021
Douglas County, Georgia	1.09	1.09	1.09	1.10
Lenoir, North Carolina	1.10	1.09	1.09	1.09
Berkeley County, South Carolina	1.10	1.10	1.10	1.11
Montgomery County, Tennessee	1.10	1.11	1.11	1.14
Jackson County, Alabama	1.10	1.11	1.12	1.16
Loudoun County, Virginia	1.09	1.08	1.09	*
Loudoun County, Virginia (2nd Facility)	1.08	1.08	1.11	*
New Albany, Ohio	1.09	1.10	*	*
Council Bluffs, Iowa	1.12	1.11	1.11	1.11
Council Bluffs, Iowa (2nd Facility)	1.08	1.08	1.09	1.09
Papillion, Nebraska	1.09	1.12	*	*
Mayes County, Oklahoma	1.10	1.10	1.10	1.11
Midlothian, Texas	1.12	1.14	*	*
The Dalles, Oregon	1.10	1.10	1.10	1.10
The Dalles, Oregon (2nd Facility)	1.07	1.07	1.06	1.07
Henderson, Nevada	1.08	1.10	*	*
Storey County, Nevada	1.17	*	*	*
Dublin, Ireland	1.08	1.09	1.09	1.09
St. Ghislain, Belgium	1.09	1.09	1.08	1.09
Eemshaven, Netherlands	1.07	1.07	1.08	1.09
Fredericia, Denmark	1.09	1.11	*	*
Hamina, Finland	1.09	1.09	1.09	1.09
Changhua County, Taiwan	1.12	1.12	1.12	1.12
Singapore	1.13	1.13	1.13	1.13
Singapore (2nd Facility)	1.18	1.20	*	*
Quilicura, Chile	1.10	1.09	1.09	1.08

The global PUE has significantly decreased since reporting on these figures began in 2008. Figure 5 details the weighted-average PUE over the past 12 months for all Google data centers, placing them among the most efficient in the world.

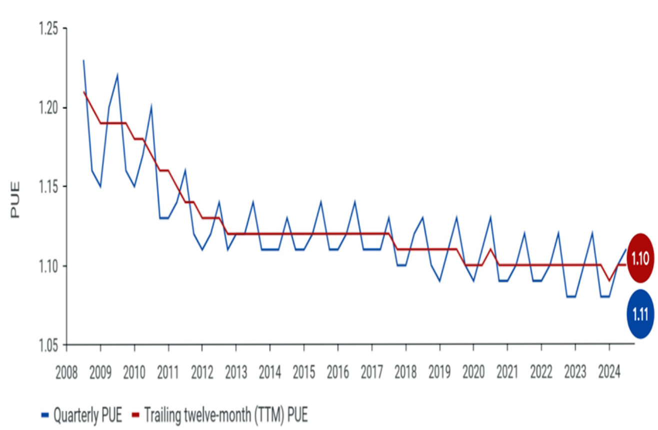

Fig. 5. Google data center PUE performance

V. RESULTS

To obtain the results, Power Usage Effectiveness (PUE) was used as a key metric, as it enabled the measurement of operational efficiency by relating total energy consumption to the energy specifically used for computing.

Figure 6 shows a box plot comparing PUE values by geographical region: North America, Europe, and Asia for 2024. This visualization highlights regional variations in PUE performance. European data centers e.g., Eemshaven, Netherlands and Dublin, Ireland tend to have lower PUE values, suggesting better efficiency, possibly due to favorable climate conditions or advanced energy optimization practices. North American data centers exhibit a wider range of values, with some locations maintaining lower PUE e.g., Council Bluffs, Iowa while others e.g., Storey County, Nevada show higher values. Asian data centers e.g., Singapore, Taiwan generally have higher PUE, possibly due to increased cooling demands in warm climates.

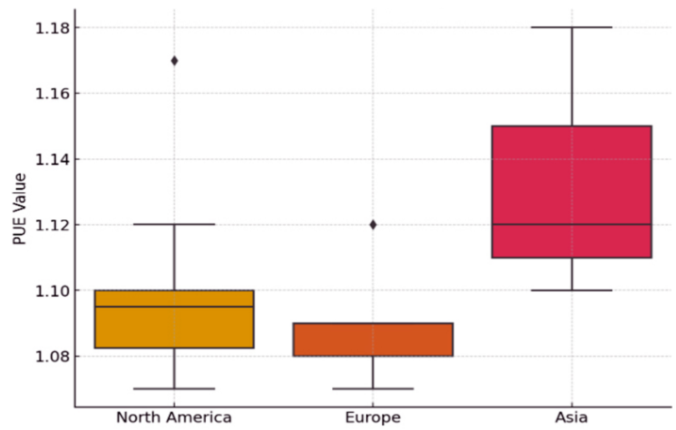

Fig. 6. PUE distribution by region

Figure 7 shows a line chart displaying the yearly trend of Power Usage Effectiveness (PUE) from 2021 to 2024 for selected campuses. This graph illustrates the evolution of PUE values across multiple years, showing whether energy efficiency has improved or declined in specific locations. A decreasing trend indicates successful implementation of energy-saving measures, while an increasing or stagnant trend may signal inefficiencies or external challenges (e.g., higher cooling requirements due to climate conditions). Notably, campuses like Loudoun County, Virginia (2nd Facility) and The Dalles, Oregon (2nd Facility) show consistent improvements, while Storey County, Nevada exhibits an increasing PUE, suggesting potential areas for further optimization.

Figure 8 shows the most data centers show minimal or no reduction in their PUE from 2023 to 2024. Some facilities improved their efficiency with reductions of up to 0.05 points in PUE. However, a small group of data centers experienced slight increases in PUE, suggesting potential challenges in implementing energy efficiency improvements or variations in load demand. The stability in PUE indicates that current strategies may be reaching their efficiency limits, requiring

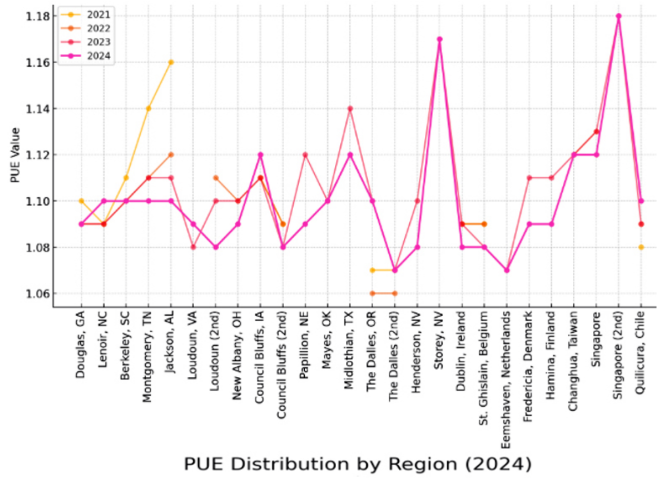

Fig. 7. PUE trend analysis

innovations in cooling systems and the use of renewable energy.

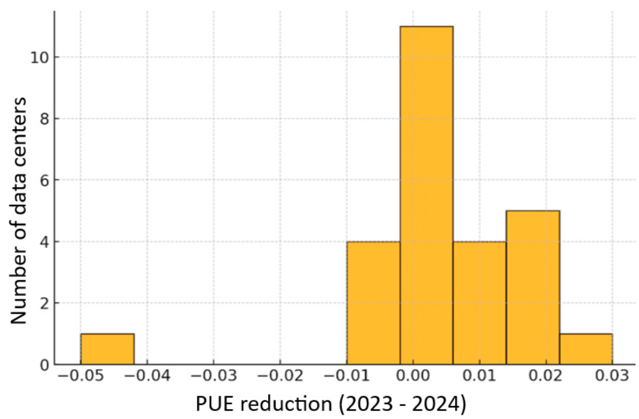

Fig. 8. Distribution of energy efficiency improvements (PUE reduction)

Figure 9 shows that Eemshaven (Netherlands) and The Dalles (Oregon, 2nd facility) have maintained a consistently low PUE, indicating sustained high operational efficiency over time. Singapore shows an upward trend, with an increase in PUE in 2023 and 2024, which may be related to climatic challenges and the need for enhanced cooling systems. Council Bluffs (Iowa) and Lenoir (North Carolina) have experienced slight fluctuations in PUE, indicating that efficiency improvements have been moderate. Overall, data centers located in colder climates appear to have an advantage in energy efficiency.

Figure 10 shows a bar chart comparing PUE reductions from 2023 to 2024 for selected locations, highlighting percentage improvements. This chart showcases how efficiency measures have contributed to reducing PUE over the past year. Singapore (2nd Facility) shows a slight increase in PUE (1.18 → 1.18), indicating limited progress, whereas Papillion, Nebraska and Loudoun County, Virginia (2nd Facility) display notable improvements. These reductions suggest that specific

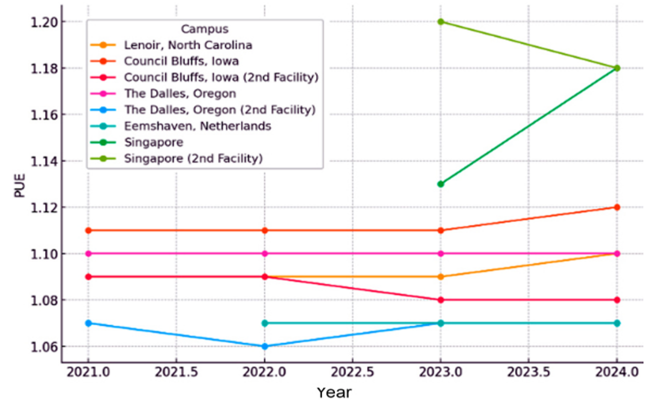

Fig. 9. Energy efficiency trends in key locations

interventions, such as improved cooling technologies or AI-based energy management, have yielded positive results in certain campuses.

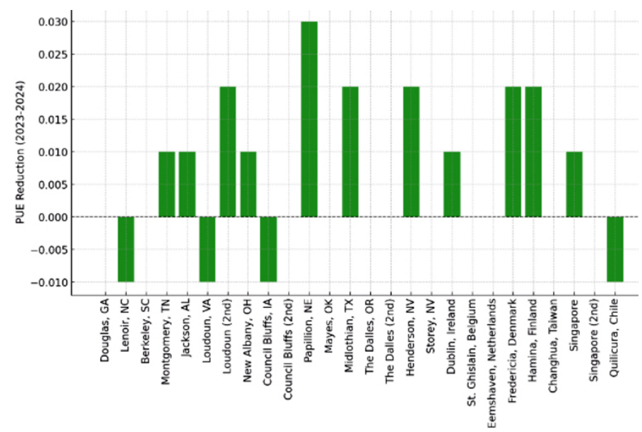

Fig. 10. Impact of efficiency measures on PUE reduction

VI. Conclusion

The integration of energy efficiency strategies and Power Purchase Agreements (PPAs) in Google's data centers has led to substantial reductions in electricity consumption and enhanced sustainability. Through advanced cooling technologies, including direct-to-chip and immersion cooling, and the implementation of artificial intelligence for energy management, Google has consistently maintained lower PUE values compared to industry benchmarks, optimizing energy use and minimizing waste. The analysis of PUE distribution by region, trend evolution over time, and the impact of specific efficiency measures confirmed that European data centers, such as those in Eemshaven (Netherlands) and Dublin (Ireland), exhibit superior efficiency, while facilities in warmer climates, like Singapore, face greater cooling challenges. Additionally, temporal analysis highlighted steady improvements in some locations, while others showed stagnation or slight increases, signaling the need for further optimization. The results emphasize that

PPAs not only secure renewable energy supply but also incentivize investments in cleaner infrastructure, contributing to overall grid decarbonization. The findings underscore that continuous innovation in cooling, AI-driven workload distribution, and energy monitoring are essential for maintaining efficiency gains and reducing environmental impact across data center operations.

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