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PV Integration and Emission Offsets in a Campus Data Center: Evidence from Seven Years of Operation

(Integración fotovoltaica y compensación de emisiones en un centro de datos universitario: evidencia de siete años de operación)

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Abstract: Data centers raise energy and environmental challenges for public and educational institutions. This paper evaluates an institutional data center at the University of Cuenca (Ecuador) supplied in part by a 35 kWp rooftop photovoltaic (PV) system operating without electrical storage since 2018. Seven years of data (2018–2024) were analyzed, including monthly records of electricity consumption, PV generation, and meteorological variables. Renewable-integration indicators are computed (demand coverage and on-site use of PV energy), and avoided CO2 emissions are estimated using official annual grid factors for Ecuador's national power system, including a sensitivity case for higher carbon intensity. Annual PV generation ranged from 24.3 to 47.3 MWh (34.4 MWh average), while annual data center consumption increased from 63.0 MWh (2018) to 149.3 MWh (2024), with a step change starting in 2020. PV coverage at the shared distribution panel (laboratory + data center) declined from 52.8% (2018) to 23.4% (2023) and 15.6% (2024), driven mainly by demand growth; in 2024, PV output was further reduced by grid outages because anti-islanding protection disconnects a grid-tied, battery-less system. Over 2018–2024, avoided emissions are estimated at 64.9–72.1 tCO2 using national emission factors (0.27–0.30 kg CO2/kWh), and 96.2 tCO2 under a 0.40 kg CO2/kWh scenario. The results support the *green data center* agenda by informing planning decisions for integrating on-site renewable generation in data centers, with emphasis on finer submetering, energy storage, and PV capacity expansion as digital workloads grow.

Keywords: green-data centers, photovoltaic energy, self-consumption, CO2 emissions, renewable integration.

Resumen: Los centros de datos plantean retos energéticos y ambientales en instituciones públicas y educativas. Este trabajo evalúa un centro de datos institucional de la Universidad de Cuenca (Ecuador), asistido por un sistema fotovoltaico (FV) en azotea de 35 kWp, sin almacenamiento, en operación desde 2018. Se analizaron siete años de datos (2018– 2024), con registros mensuales de consumo eléctrico, generación FV y variables meteorológicas. Se estimaron indicadores de integración renovable y las emisiones de CO2 evitadas mediante factores oficiales del sistema eléctrico nacional, incluyendo un análisis de sensibilidad para un escenario de mayor intensidad de carbono. La generación FV anual varió entre 24,3 y 47,3 MWh (promedio 34,4 MWh), mientras que el consumo anual del centro de datos aumentó de 63,0 MWh (2018) a 149,3 MWh (2024), con un cambio de nivel a partir de 2020. La cobertura FV del consumo compartido (laboratorio + centro de datos) disminuyó de 52,8 % (2018) a 23,4 % (2023) y 15,6 % (2024), principalmente por el crecimiento de la demanda; en 2024, además, la generación FV se redujo por desconexiones durante cortes programados de red. En el periodo 2018–2024 se estimaron 64.9–72.1 tCO2 evitadas con factores nacionales (0.27–0.30 kg CO2/kWh), y 96,2 tCO2 bajo un escenario de 0,40 kg CO2/kWh. El estudio aporta insumos cuantitativos para la agenda de *green data centers* y respalda decisiones de planificación orientadas a incorporar

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generación renovable en centros de datos, con énfasis en submedición, almacenamiento e incremento de capacidad FV conforme crecen las cargas digitales.

Palabras clave: centros de datos sostenibles, energía fotovoltaica, autoconsumo, emisiones de CO2, integración renovable.

1. INTRODUCTION

Data centers account for a growing share of electricity demand as digital services, cloud computing, and data storage expand. Although server power management and facility thermal design have improved over time, total consumption may still increase when computational capacity and service availability grow faster than efficiency gains. Sustainability assessments extend beyond electricity use to include cooling-related water consumption and electronic waste streams [1], [2]. These issues are relevant for university data centers, where infrastructure modernization is often shaped by budgetary and operational constraints while service demand continues to grow [3], [4]. In this context, the notion of *green data centers* has shifted from a broad aspiration to a set of design and operational practices tied to measurable sustainability objectives. Recent frameworks emphasize energy efficiency together with coordinated management of supporting resources and operational decisions (e.g., virtualization and consolidation policies, cooling strategies, and continuous energy monitoring) to reduce overall environmental impacts [1]. For medium-scale facilities, a recurring theme is that renewable integration alone is insufficient unless it is paired with instrumentation and data services that make energy use, thermal conditions, and workload behavior jointly observable and usable for operational control [5], [6].

Photovoltaic (PV)-assisted data centers are feasible in regions with adequate solar resources, given the modularity of PV deployment and the opportunity to increase on-site self-consumption. However, solar generation is variable, whereas computing services and cooling requirements are continuous and often time-sensitive. Prior research has therefore emphasized integrated monitoring and cyber-physical management architectures that combine PV production, weather conditions, subsystem power measurements (information technology (IT) equipment and cooling), and workload descriptors—including container-level visibility—to support operational decision-making [5], [6]. The literature also examines algorithmic approaches to reduce grid electricity use and carbon emissions through workload shifting and demand-response participation. Deep reinforcement learning has been proposed as a controller to coordinate workload scheduling and cooling under stochastic conditions and onsite renewables [7], while hierarchical load models that capture coupled electrical–thermal–performance behavior have been introduced to improve demand-response quality without driving inefficient operating points [8]. Despite this progress, deployment in production environments remains limited; recent reviews report that overly complex frameworks, broken abstraction layers, narrow reliance on batch workloads, and weak incentives continue to slow adoption in operational settings [9].

This study provides empirical evidence in this area by analyzing an operational institutional data center at the University of Cuenca, Ecuador, partially supplied by a 35 kWp rooftop PV system directly connected to the internal distribution panel. The facility has operated continuously since 2018, enabling a longitudinal assessment over a seven-year observation window (2018–2024). We characterize the temporal evolution of electricity consumption and PV generation, quantify the renewable contribution to the facility energy balance, and estimate the associated reduction in carbon emissions due to displacement of grid electricity. By focusing on an educational, medium-scale installation in Latin America, the work complements prior conceptual and algorithmic studies with measured, long-term performance evidence to inform planning and replication in similar public sector settings [1], [3], [5].

2. MATERIALS AND METHODS

2.1. Infrastructure description

The data center analyzed in this study is located at the University of Cuenca (Cuenca, Ecuador) and has operated continuously since 2018, supporting institutional computing services, virtualized workloads, storage, and internal academic platforms. The facility is partially supplied by a rooftop photovoltaic (PV) plant with an installed capacity of 35 kWp, installed on the main building [10]. The PV installation comprises both polycrystalline and monocrystalline silicon modules. Most of the PV arrays are mounted in fixed structures with a tilt angle of 5° and a north-facing orientation, which is a common configuration for maximizing solar energy capture under local conditions in the southern hemisphere. The PV system is connected directly to the internal low-voltage distribution panel and operates without electrical storage (battery-less configuration); therefore, its contribution depends on real-time irradiance conditions.

The information technology (IT) room follows a rack-based architecture. According to the as-built layout, the installation comprises eight racks with a rated capacity of 5 kW per rack, arranged in four pairs to support operational organization and cable and airflow management. Thermal control is provided by four precision air-conditioning (A/C) units (Air Conditioner– B1), each rated at 21 kW of electrical power and equipped with electric heating and humidification. These units maintain the indoor environmental conditions required for reliable IT operation and provide redundancy at the cooling-system level. Table 1 summarizes the nameplate electrical capacities used in this work to characterize the infrastructure.

Table 1. Installed electrical capacity of the main subsystems in the Microgrid Laboratory (LMR) data center (nameplate values).

Subsytem	Qty	Unit (kW)	Total (kW)	Notes
IT racks (servers, storage, networking)	8	5	40	Racks arranged in four pairs
Precision A/C (Air Conditioner– B1)	4	21	84	Includes electric heating and humidifier
Total (IT + cooling)	**-**	**-**	**124**	Excludes auxiliaries (uninterruptible power supply (UPS) losses, lighting, etc.)

The values reported in Table 1 represent nameplate ratings (design capacities), not continuous operating demand. In practice, the instantaneous IT power depends on server utilization and the equipment population within each rack, while cooling demand varies with indoor and outdoor conditions and the control strategy of the A/C units (e.g., compressor cycling or modulation). In addition, redundancy policies may keep one or more units in standby or operating below their maximum rating. As a result, the measured electrical demand of the facility can be lower than the sum of nameplate ratings during normal operation.

To document the physical arrangement and support interpretation of the energy measurements, this section includes: (i) photographic evidence of the data center room and the rooftop PV installation (Figure 1 and Figure 2); (ii) a schematic representation of the internal composition of the data center (IT racks and cooling subsystems) used as a reference model for the energy balance discussion (Figure 3); and (iii) the single-line diagram of the electrical layout of the studied installation (Figure 4), which summarizes the net-balance operating principle. Under normal grid availability, the data center and the remaining laboratory loads draw electricity from the distribution network and are supplemented in real time by the on-site PV production at the shared low-voltage panel. When PV generation exceeds instantaneous demand, the surplus can be exported to the public grid, whereas when demand exceeds PV output, the deficit is supplied by the grid. During public-grid outages, the grid-tied PV system is disconnected by anti-islanding protection and stops generating; in that condition, continuity of data center operation is maintained by thermal generator sets.

Figure 1. Photograph of the University of Cuenca data center.

Figure 2. Rooftop PV installation (35 kWp) connected to the internal distribution panel.

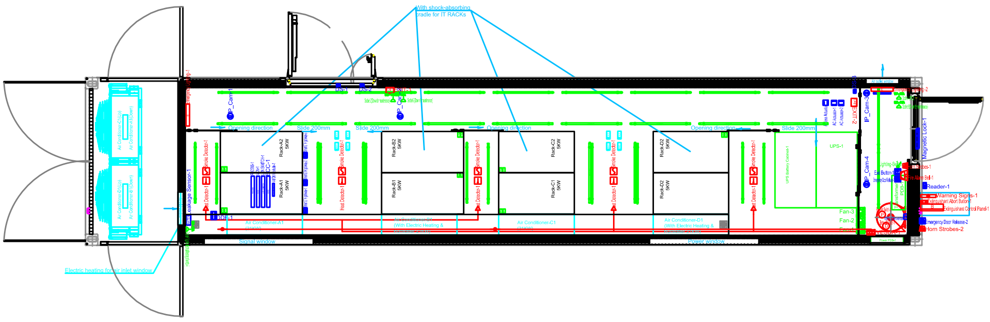

Figure 3. Internal composition of the data center used as a reference for the energy assessment (IT racks and cooling subsystems).

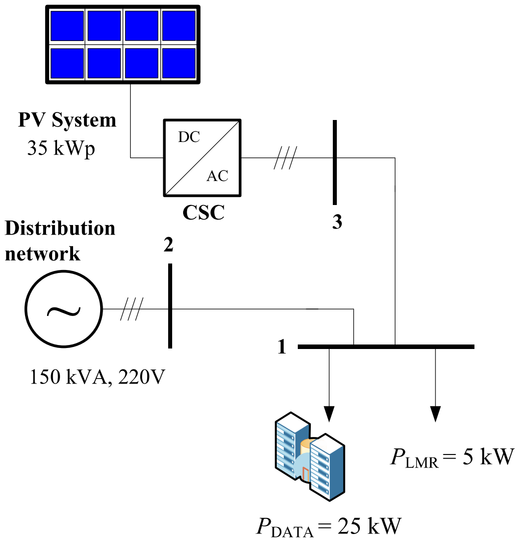

Figure 4. Electrical layout of the Microgrid Laboratory (LMR).

2.2. Data sources

The analysis uses a seven-year dataset spanning January 2018 through December 2024. It integrates electricity demand, PV production, and environmental records to characterize long-term behavior of the LMR facility and its onsite renewable supply. Electricity consumption was obtained from the internal metering infrastructure, which provides monthly and annual energy totals at the facility level for longitudinal assessment and interannual comparison. In parallel, PV generation data were retrieved from the inverter monitoring platform and cross-checked against local dataloggers connected to the DC/AC conversion stage. This cross verification reduces the likelihood of missing values and improves traceability when performance changes are observed over time.

To provide context for PV production variability and to support interpretation of seasonal and interannual trends, local meteorological measurements were also incorporated. Solar irradiance and ambient temperature records were collected from a nearby weather station operated by the Faculty of Engineering. These environmental series are not used to predict generation; instead, they provide a physical reference for expected fluctuations and help distinguish resource-driven changes (e.g., irradiance patterns) from system-driven changes (e.g., operational events).

A relevant methodological aspect is that the PV plant supplies a shared low-voltage panel feeding both the data center and auxiliary laboratory loads. Therefore, the “total demand” used in the PV coverage metrics corresponds to the combined energy consumption of the Microgrid Laboratory and the data center. To isolate the operational demand of the data center for subsequent analyses, a dedicated measurement campaign was conducted at the data center three-phase service entrance. The Results section reports both views—aggregate facility demand and data center demand—to avoid conflating infrastructure-level behavior with IT-room operation.

2.3. Renewable energy share assessment

On-site PV integration is quantified using complementary indicators that describe (i) the renewable fraction of the total demand supplied by the shared panel and (ii) the extent to which PV production is used locally. First, the Energy Share (ES) is computed as the ratio between PV generation and total electricity demand over a given accounting window (monthly, then aggregated annually). This indicator summarizes the renewable contribution relative to the energy needs of the supplied loads.

Because behind-the-meter PV generation can be consumed locally or exported to the public grid, the analysis distinguishes between PV generation and PV utilization. Self-consumption is defined as the fraction of PV energy used within the supplied loads, excluding any potential feed-in. Following the framework in [1], two indicators are reported:

- **Green Share (GS):** the proportion of electricity demand met by on-site PV generation within the same accounting period.
- **Renewable Energy Utilization Rate (REUR):** the fraction of total PV generation that is consumed locally within the supplied loads.

All indicators are computed on a monthly basis to preserve seasonal information and then aggregated annually to identify long-term trends in energy integration, operational stability, and PV-to-load matching. When interpreting the indicators, the manuscript distinguishes between metrics computed at the shared-panel level (laboratory + data center) and those derived from the dedicated data center measurements.

2.4. Avoided emissions estimation

Avoided carbon emissions are estimated using a displacement approach in which PV electricity consumed on-site offsets an equivalent amount of electricity that would otherwise be supplied by the public grid. For consistency with institutional greenhouse-gas (GHG) accounting, this work adopts the official annual grid-average emission factor for Ecuador Continental reported in the national "Factor de Emisión de CO2 del Sistema Nacional Interconectado (SNI)" series coordinated by the Operador Nacional de Electricidad (CENACE) [11], [12], [13]. This choice aligns with the location-based method described in the GHG Protocol Scope 2 Guidance, which recommends using grid-average emission factors to represent the average emissions intensity of the electricity system where consumption occurs [14]. The same national reports also include project-oriented factors based on the UNFCCC combined-margin methodology (Tool 07) [15]; however, because the objective here is to quantify avoided emissions under operational self-consumption (behind-the-meter PV displacing grid electricity at the point of supply), the grid-average factor is the appropriate reference.

Avoided emissions are calculated as shown in Equation (1):

$$E_{avoided} = E_{PV,used} \times EF_{grid} \tag{1}$$

where $E_{PV,used}$ is the PV electricity consumed locally by the supplied loads and EF_{grid} is the annual grid emission factor (kg CO2/kWh). This formulation follows common reporting practice for renewable displacement assessments and is consistent with the methodologies discussed in [7], [8]. When presenting results, avoided emissions are reported at monthly resolution and summarized annually to compare environmental outcomes across years.

2.5. Additional indicators

Beyond energy and emissions, the study considers complementary metrics when the required information is available in the monitoring records. In particular, an economic reference can be provided through the levelized cost of energy (LCOE) of the PV system, computed from capital expenditure, operation and maintenance costs, and cumulative electricity production over the assumed system lifetime. In addition, an operational environmental-intensity indicator can be discussed using Carbon Usage Effectiveness (CUE), relating carbon emissions to IT energy use. If these variables cannot be supported with sufficient data granularity or traceability for the study period, the manuscript limits its reporting to the energy-share and avoided-emissions indicators described above and states explicitly which inputs were not available.

3. RESULTS

3.1. Photovoltaic Generation Analysis

The annual and seasonal performance of the 35 kWp rooftop PV system was evaluated for 2018–2024 using inverter-reported production data cross-checked with local dataloggers. Table 2 summarizes the annual energy yield and the corresponding capacity factor, which represents the effective utilization of the installed capacity in each year. Over the study period, the PV system produced an average of about 34.4 MWh per year. Year-to-year variation reflects changes in operating conditions and solar resource availability. The highest annual output occurred in 2022 (47.3 MWh; capacity factor 15.4%), whereas the lowest occurred in 2024 (24.3 MWh; capacity factor 7.9%). The 2024 value must be interpreted in context because it coincided with an unusual operating period in Ecuador, with extended scheduled power outages associated with the national electricity crisis. Since the PV plant operates in a grid-tied, battery-less configuration, inverter anti-islanding protection disconnects generation during grid outages. As a result, the PV energy recorded by the monitoring system can drop even when solar resource is available. During those periods, the data center was supplied mainly by on-site generator sets, and the 2024 PV output does not reflect typical operation under continuous grid availability.

Table 2. Annual PV generation and capacity factor of the 35 kWp rooftop system (2018–2024).

Year	PV generation (kWh)	Capacity factor (%)
2018	34 665.1	11.3
2019	33 004.5	10.8
2020	34 309.6	11.2
2021	29 545.2	9.6
2022	47 289.0	15.4
2023	37 391.7	12.2
2024	24 257.0	7.9

At the seasonal scale, the monthly profiles presented later follow the local climatic cycle, with recurring periods of higher production during months with greater solar resource and reduced cloudiness. To further support this interpretation, Figure 5 compares the annual PV energy production with the annual solar irradiation measured by a meteorological station installed on the rooftop of the same building where the PV system is located. The results show a strong correspondence between both variables throughout most of the study period, indicating that interannual variations in PV generation are largely explained by the available solar resource. Although the irradiation data are presented at annual resolution, the Andean climate of Cuenca is characterized by alternating sunny and cloudy periods, influenced by seasonal rainfall patterns and regional meteorological anomalies such as El Niño-related variability, drought conditions, and prolonged dry spells. In this context, the higher irradiation observed in 2024 is consistent with reduced rainfall and clearer-sky conditions during the national drought period. However, a noticeable divergence appears in 2024, when PV production decreased disproportionately relative to the measured solar irradiation. This behavior is consistent with the extended scheduled power outages experienced in Ecuador during the national electricity crisis. Thus, the mismatch between irradiation and PV production in 2024 is mainly attributed to power outages associated with the drought-driven low-water period, rather than to a reduction in the available solar resource. Because the PV system operates in a grid-tied, battery-less configuration, anti-islanding protection disconnects the inverters whenever the public grid is unavailable, preventing energy production even under favorable solar conditions. Therefore, the 2024 reduction in PV output should not be interpreted as a consequence of diminished solar resource availability but rather as the result of operational restrictions imposed by prolonged grid interruptions. This seasonal structure is used in the following subsections to interpret PV-to-load matching and the resulting renewable utilization indicators.

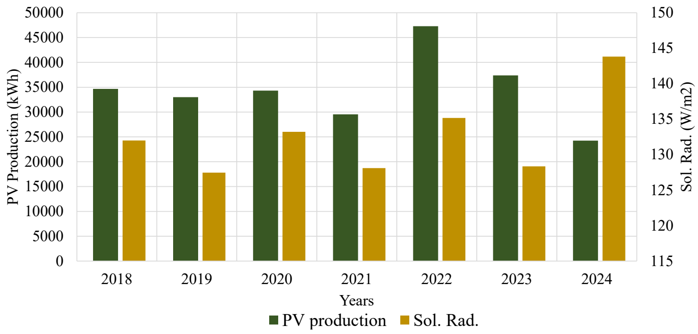

Figure 5. Annual solar irradiation measured at the rooftop meteorological station and annual PV energy production of the 35 kWp system (2018–2024).

3.2. Data Center Energy Consumption

Electricity demand at the data center increased over 2018– 2024, consistent with the expansion of institutional digital services and the growing deployment of virtualized workloads. Although the overall trajectory is upward, the series presents distinct phases rather than a uniform, linear increase. Consumption remained relatively stable during the first two years of operation (2018–2019), followed by a pronounced increase in 2020–2021, consistent with the commissioning of additional computing and storage resources and the consolidation of new services. From 2022 onward, the facility operated at a higher demand level, with year-to-year variation associated with operational scheduling, workload dynamics, and infrastructure management practices.

Seasonal behavior is also evident in the monthly records. Higher energy use typically aligns with active academic periods (March–July and September–December), when user access, hosted platforms, and institutional services intensify. Lower consumption is observed during semester breaks, when user activity decreases and some computational tasks are reduced or rescheduled. In addition to workload-related drivers, the cooling subsystem contributes to seasonal variability because heating, ventilation, and air conditioning (HVAC) operation depends on indoor setpoints and ambient conditions and may respond differently during warmer or more humid weeks.

The PV plant supplies a shared low-voltage panel feeding both the data center and auxiliary laboratory loads. Historical energy records indicate that the data center accounts for the dominant share of the combined Microgrid Laboratory + data center electricity demand; therefore, changes in aggregate facility energy largely follow data center operation. To support a clear separation between data center demand and other laboratory loads, a dedicated measurement campaign was conducted at the data center three-phase service entrance. This campaign provides an operational reference for typical daily energy use and weekday–weekend differences, which is later used to validate the allocation assumptions applied in the energy-share indicators.

Table 3 summarizes the annual electricity consumption of the data center for the analyzed period. A joint visualization comparing PV generation and data center demand is presented in a subsequent subsection to support the statistical interpretation of renewable contribution under evolving load conditions.

Table 3. Annual electricity consumption of the University of Cuenca data center (2018–2024).

Year	Data center consumption (kWh)
2018	63 019.62
2019	66 220.96
2020	112 013.29
2021	111 484.00
2022	145 045.34
2023	153 153.91
2024	149 261.40

In addition to the historical monthly and annual records, the measurement campaign at the data center three-phase service entrance was used to characterize a representative short term operating profile and to support the separation between data center demand and auxiliary laboratory loads. The campaign covered seven consecutive days (including working days and the weekend) and recorded the daily energy exchanged at the data center point of common coupling. Figure 6 shows the resulting weekly pattern: daily consumption remains relatively stable during weekdays, with a moderate reduction on Saturday and Sunday, consistent with lower user activity and reduced workload intensity outside regular institutional schedules.

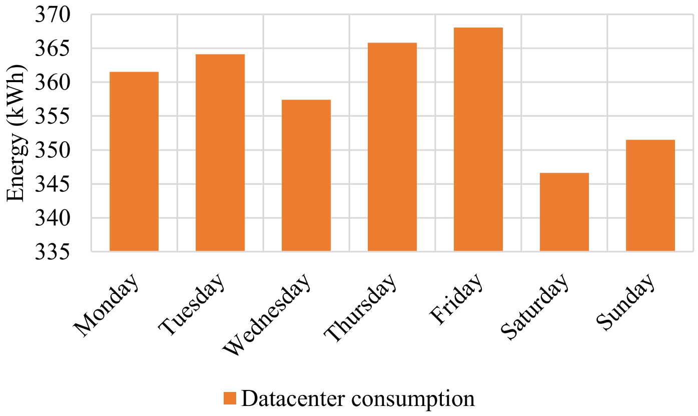

Figure 6. Typical weekly data center energy consumption measured at the three-phase service entrance during a 7-day campaign (weekday vs weekend operation).

3.3. Energy Balance and PV Contribution

The energy balance compares the annual PV production of the 35 kWp rooftop plant against the electricity demand supplied at the same low-voltage panel. Figure 7 summarizes this balance by displaying PV generation and data center consumption together, which supports interpretation of how the renewable contribution changes as institutional workload evolves over time. While PV production remains within the same order of magnitude across the monitoring horizon, data center demand shows a step increase starting in 2020 and remains higher thereafter. Consequently, the relative contribution of PV declines in years with higher IT activity, even when PV yield is stable.

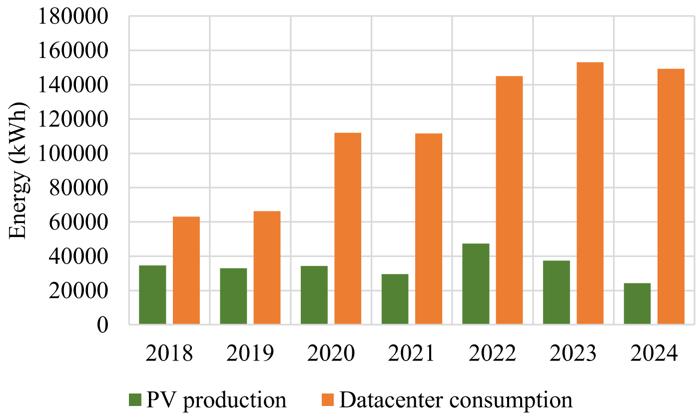

Figure 7. Annual energy balance between PV generation and data center electricity consumption (2018–2024).

Following the indicators defined in Section 2, PV coverage of the total supplied demand (Microgrid Laboratory + data center) ranges from 52.8% (2018) to 15.6% (2024). The decline after 2019 is explained mainly by growth in electricity demand rather than by a persistent reduction in PV output. Over 2018–2024, cumulative PV generation reached 240.5 MWh, representing on-site renewable electricity produced during institutional operation.

Results for 2024 require careful interpretation. That year coincided with an unusual national operating context in Ecuador characterized by extended scheduled power outages. Because the PV system is grid-tied and battery-less, inverter anti-islanding protection disconnects PV generation during grid interruptions, which can reduce recorded PV energy even when solar resource is available. During these periods, data center continuity relied mainly on on-site thermal generator sets. For this reason, 2024 is treated as an outlier year in the discussion, and results are also interpreted using the pre-crisis years (2018–2023) as a reference baseline.

The observed PV contribution reduces grid electricity purchases and associated operating costs and increases avoided emissions. The corresponding economic and environmental impacts are quantified in the subsequent subsections using the tariff and emission-factor assumptions described in the Methods section.

3.4. Emission Reduction

Avoided carbon emissions were estimated using a displacement approach in which PV electricity used on-site offsets an equivalent amount of electricity that would otherwise be supplied by the public grid. Consistent with Section 2, avoided emissions over a given accounting period are computed according to Equation 2:

$$E_{avoided} = E_{PV,used} \times EF_{grid} \tag{2}$$

where $E_{PV,used}$ is the PV energy consumed behind the meter and EF_{grid} is the grid-average emission factor (kg CO2/kWh). As the PV system operates in a battery-less, grid-tied configuration and the supplied loads are large relative to PV capacity, self-consumption is close to 100% during normal operation. Therefore, for annual accounting, E_{PV}, used is approximated by the total measured PV generation when export is negligible. If export data are available, the same formulation applies by subtracting exported energy from total generation.

Baseline avoided emissions using official Ecuadorian factors

Grid emission factors were obtained from the annual reports published by Ecuador's electricity operator (CENACE) and environmental authorities (MAATE), following the GHG

Protocol guidance for institutional inventories. These factors reflect the average carbon intensity of the national electricity mix (Sistema Nacional Interconectado, SNI) and are suitable for location-based emission accounting in public-sector facilities. For the 2018–2024 period, this study adopts an estimated range of 0.27–0.30 kg CO2/kWh to reflect interannual variability and reporting conventions [11], [12], [13].

Table 4 reports the resulting annual range, computed by applying the lower and upper emission-factor bounds to each year's PV generation. Over 2018–2024, cumulative avoided emissions fall within the range given by Equation (3):

$$E_{avoided,tot} \in [64{,}9, 72{,}1]\ tCO_2 \tag{3}$$

which represents the net reduction in emissions associated with PV-based self-consumption under national grid conditions.

Table 4. Avoided emissions estimated from annual PV generation using the national emission-factor range (0.27–0.30 kg CO2/kWh).

Year	PV used (kWh)	Avoided emissions (tCO_2)	
		0.27 kg/kWh	**0.30 kg/kWh**
2018	34 665.1	9.36	10.40
2019	33 004.5	8.91	9.90
2020	34 309.6	9.26	10.29
2021	29 545.2	7.98	8.86
2022	47 289.0	12.77	14.19
2023	37 391.7	10.10	11.22
2024	24 257.0	6.55	7.28
Total	**240 462.1**	**64.92**	**72.14**

Interannual variability and interpretation (including 2024)

Year-to-year variation in avoided emissions is driven primarily by changes in PV generation. In this dataset, the highest annual reduction occurred in 2022 (14.2 tCO2), while the lowest corresponds to 2024, which reflects an atypical operating context. During that year, Ecuador experienced extended scheduled grid outages related to a national electricity supply crisis. Because the PV system is grid-tied, inverter anti-islanding protection prevented operation during interruptions, even under available solar resource. Consequently, 2024 results do not represent standard PV performance under continuous grid availability. During those periods, data center operation relied mainly on on-site thermal generators, which fall outside the emission displacement calculation. For consistency, the Discussion section treats 2024 as an outlier and uses 2018–2023 as a baseline for typical grid-tied operation.

Sensitivity to higher carbon intensity scenarios

To assess the influence of grid carbon intensity, the avoided-emissions estimate was recalculated using a more conservative scenario aligned with thermal-dominated generation contexts. Under EF_{grid} = 0.40 kg CO2/kWh, cumulative avoided emissions rise to the value given by Equation 4:

$$E_{avoided,tot}\,(0.40) = 96.2\ tCO_2, \tag{4}$$

illustrating the increased environmental benefit of PV when the displaced grid electricity has higher emission content. This sensitivity analysis supports comparisons across regions and underscores the relevance of PV integration under evolving generation mixes.

4. DISCUSSION

This study quantified the long-term interaction between a rooftop PV plant and an institutional data center operating continuously since 2018. The results offer a practical perspective on sustainability outcomes in a university setting: a measurable share of electricity demand is supplied by onsite renewables, PV generation is largely self-consumed due to the persistent base-load behavior of the data center, and avoided emissions can be estimated under the national electricity mix using recognized accounting practices. The use of complementary indicators such as Green Share (GS) and Renewable Energy Utilization Rate (REUR) (Murino et al., 2023) distinguishes between the share of demand met by renewables and the fraction of PV generation consumed onsite. This distinction is especially relevant in the LMR configuration, where the PV system supplies a shared low-voltage panel and the data center dominates the total demand. Additionally, the dedicated three-phase measurement campaign at the data center entrance provides a reference for typical weekday–weekend operation and supports load disaggregation.

The PV–demand balance shows that the decline in PV coverage after the initial years is primarily driven by increased consumption (not reduced output), particularly following a step change in 2020. This is consistent with institutional growth through virtualization, storage expansion, and service consolidation. The analysis also clarifies why real operating demand is often below nameplate ratings: IT power depends on utilization levels and rack population, and precision A/C units modulate input based on thermal loads and setpoints, with redundancy strategies keeping some units partially loaded or on standby.

The operating conditions in 2024 must be interpreted separately. Extended scheduled outages during Ecuador's electricity crisis led to a temporary loss of PV contribution due to anti-islanding protections in the battery-less, grid-tied configuration. During these periods, the facility relied on thermal backup generators, which are excluded from the emission reduction calculation. This contrast highlights the difference between sustainability under normal grid operation and resilience during supply disruptions.

Regarding emissions, while the grid in Ecuador has traditionally been low in carbon intensity due to hydropower dominance, cumulative avoided emissions remain relevant over multi-year operation. The estimates in this study are consistent with institutional reporting frameworks such as the GHG Protocol, using official annual grid-average emission factors published by CENACE and MAATE [11], [12]. The sensitivity analysis shows that avoided emissions increase in proportion to the grid's carbon intensity, reinforcing the environmental value of PV as generation mixes evolve.

The findings support two upgrade pathways that could enhance both indicator performance and operational resilience: (i) incorporating energy storage to increase PV utilization through time-shifting and to enable autonomous operation during outages via islanding-capable control; and (ii) scaling PV capacity to match post-2020 demand growth and recover earlier coverage levels as digital workloads continue expanding.

Limitations and opportunities for future work are tied to data granularity and operational traceability. Extending submetering to separate IT loads, cooling systems, and auxiliary circuits would allow more refined energy allocation and enable metrics such as Carbon Usage Effectiveness (CUE). Incorporating inverter status logs and maintenance records would improve interpretation during abnormal periods. Beyond hardware upgrades, future studies may explore workload-aware scheduling and cooling setpoint optimization, supported by data center infrastructure management (DCIM) tools aligned with institutional service delivery and energy availability.

5. CONCLUSIONS

This work evaluated seven years of operation (2018–2024) of a university data center partially supplied by a 35 kWp rooftop PV plant. Historical energy records, PV monitoring data, and local environmental measurements were combined to characterize long-term performance and renewable contribution. The results indicate that on-site PV generation supplies a measurable share of the facility's energy needs and supports sustained avoided emissions. They also show that the evolution of demand, in addition to PV yield, determines the renewable fraction as institutional digital services expand. The study further clarifies the practical difference between nameplate ratings and operating demand in data center environments, where IT utilization, cooling control, and redundancy policies lead to power levels below installed capacity during normal operation. The operating conditions observed in 2024, marked by extended grid outages, illustrate the limitations of a battery-less, grid-tied PV configuration and motivate upgrades oriented to resilience.

Finally, the analyzed facility provides a reference for campus digital infrastructure supplied by on-site renewables, and the reported indicators point to improvement pathways through enhanced submetering, integration of energy storage to increase PV utilization and support operation during outages, and potential scaling of PV capacity to align with growing workloads.

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