

Net-Zero Energy Strategies for Data Centers: A Comprehensive Review, Challenges and Future Directions

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Abstract

Rapid deepening of digitization, cloud computing and artificial intelligence has led to a spurt in data center energy demands, giving rise to environmental issues and sustainability challenges. The paper discusses methods of creating the Net-Zero Energy Data Centers (NZEDC) that meet the ASHRAE specifications, such as integration of renewable energy, low-emission HVAC systems with free cooling, waste heat recovery, rooftop photovoltaic system and Power Utilization Effectiveness (PUE). An elaborate case study on a 100-kW data center in Phoenix, Arizona is given. The numerical figures prove that PUE decrease between 1.5 to 1.3 leads to annual energy savings of 175,200 kWh. Optimization of the cooler raises COP to 4.5/3.0 -33.33 percent less cooling power is used. It takes a net-zero of 633 kW of solar PV capacity covering 4,112 square meters and 600 kWh of battery storage. Over 613,200 kg of CO₂ that would be emitted each year can be offset by waste heat recovery, which is enough to heat 153 homes. Sensitivity analysis indicates PUE range of 1.2 to 1.6 will alter PV requirements of 195 kW. The most important technical, infrastructure, and regulatory issues are described. The most promising areas of research are AI-powered energy management, carbon accounting of lifecycle, and sustainability metrics standardization. The result shows that the integrated design solution could serve as a viable way to reach net-zero operation, as well as keep the equipment reliable and offer a framework, which could be used to scale to develop environmentally responsible data centers.

Introduction

The modern digital economy, e-commerce, cloud computing, and AI applications in the United States have augmented the demand for data storage. Data centers are power-consuming areas that enable storage, receipt, processing and transmission of digital data. The 2014–2016 annual data center energy consumption in the U.S. has been 60 TWh, which has been a negligible growth trajectory since approximately 2010. High-capacity servers and high-powered GPUs started to make up a large part of the data center, and the overall data center electricity consumption started to grow in 2017. As of 2018, the data centers had 1.9 percent of the total annual electricity use in the US. The use of energy still was on an accelerating pace at about 4.4% of total U.S. power consumption. The data center installation that is growing annually and is projected to consume a portion of up to 6.7 percent to 12.0 percent of all U.S. electricity consumption projected in 2028 to fulfill the AI workload, is estimated to consume a significant amount of energy (Shehabi, A., Smith, S.J., Hubbard, A., Newkirk, A., Lei, N., Siddik, M.A.B., Holecek, B., Koomey, J., Masanet, E., Sartor, D. 2024).

Increasing data center infrastructure responsible for carbon emission. In a 2024 study (Shehabi, A., Smith, S.J., Hubbard, A., Newkirk, A., Lei, N., Siddik, M.A.B., Holecek, B., Koomey, J., Masanet, E., Sartor, D. 2024), it was discovered that the data centers released 31.5 million tons of carbon emissions in 2018 and the release of 105 million metric tons of carbon emissions by 2024, which means that it emitted a percentage of carbon emissions of about 2% in the U.S. This constitutes a tripled number of emissions since the growth in data centers has increased to 5,381 facilities since 2018 (Miguel Yañez-Barnuevo, 2025).

Here, power consumption breakdown is explicated about conventional data centers. A mechanical cooling system consumes the largest share of about 50%, highlighting that cooling is the major energy consumption. Critical loads representing the main operational energy use such as IT hardware components, telecommunications equipment, storage devices, servers, routers, computers, etc., as well as the security systems, fire and monitoring systems account for 36%. The overhead needed to provide power reliability and backup is indicated as an additional 11% in the uninterruptible power supplies (UPS) inefficiency and battery as a charge. Lighting consumes only 3 percent of the entire energy meaning that it has a very slight influence as opposed to other systems (Richard L. Sawyer).

Over the last few years, numerous methods have been invented to minimize the environmental impact of data centers. Examples of techniques arising via this evolution are, the minimization of energy usage by air conditioners using computational fluid dynamics (numerical modelling) (R. Schmidt, 2001); energy efficient server platform and resilient power control options (R. Raghavendra, P. Ranganathan, V. Talwar, Z. Wang, X. Zhu, 2008); layout of in-cabinet IT machinery in hot and cold aisles (C. Patel, R. Sharma, C. Bash, A. Beitelmal, 2002). Some solutions in this advancement involve the dynamic thermal management of air-conditioners using thermally intelligent and energy-intelligent virtualized workload placement at the computer racks aisle containment (H. Chen, M. Kesavan, K. Schwan, A. Gavrilovska, P. Kumar, Y. Joshi, 2011); and the merging of the data center with ambient conditions with economizers or on-site renewable energy generation such as wind and solar photovoltaics (B. Watson, A. Shah, M. Marwah, C. Bash, R. Sharma, C. Hoover, T. Christian, C. Patel, 2009). Lots of machines with low utilization. As a result, irrespective of the loads, the data center consumes a significant amount of power and cooling resources. To tackle these issues an effective approach of Net Zero Energy Data Centers (NZEDCs) emerged. Which involves smart design, energy-saving and non-renewable energy integration. An opportunity exists to offer data center management solutions which are concerned with integrating energy and cooling sources (supply) with the IT workload (demand) throughout the data center lifecycle.

The Net-Zero Energy Building (NZEB) phenomenon constituted is based on the fundamental principle that a building with a yearly energy intake equivalent to the renewable energy supply, and whose energy needs are minimal provided that within the boundaries of the building stay constant. Energy efficiency would help in attaining the low energy requirements. Examples of these include, but are not limited to, high-efficiency heating, ventilation, and air-conditioning system, natural ventilation, evaporative cooling, geothermal energy use, daylighting, insulation and passive solar heating (Pless, S., & Torcellini, P. (2010)). The NZEB development started in the late 20th century, inspired by energy security issues and development of building energy modelling. At the beginning of the 2000s, new buildings required NZEBs as required by the EU Energy Performance of Buildings Directive.

The NZEB can be expressed as follows:

$$\text{NZEB balance} = |\text{weighted supply}| - |\text{weighted demand}| = 0$$

The concept of NZEB is visually depicted as depicted in Fig. 1, (M.A. Hannan, M. Faisal, P.J. Ker, L.H. Mun, K. Parvin, T.M.I. Mahlia, F. Blaabjerg, 2018) where the weighted energy demand and weighted

energy supply is plotted on the x- and y-axis, respectively. NZEB is attained after a period when the weighted energy production is equal to or higher than the weighted energy demand. Weighted supply of energy appears on the vertical axis and the weighted demand of energy on the horizontal axis whereas on-site generation, received energy, building load, and exported energy appear on the graph to indicate how energy moves through the system over a month. The balance of imports and exports of energy is the balance between what is imported and what is sent to the grid. Monthly net load and net generation show deficits or excess. The self-consumption rates show the extent of energy generated on-site and the resource of energy efficiency to help lower demand relative to reference building.

The concept of Net Zero Energy Building (NZEB) shown in Fig. 2 provides a good methodological foundation to build the net zero energy data centers. Both ideas are based on reducing energy consumption as of efficiency and the attainment of balance between the delivered and renewable energy annually. NZEB principles can be modified to apply to the dominant loads in a data center, which include IT equipment, HVAC systems, lighting and power conversion losses. The use of NZEB energy balance indicators like energy demand, self-consumption, import-export indicators, PUE, and the renewable energy integration can be applied to assess performance in a systematic way (S. Shrestha, 2015). Combined high-level HVAC measures, waste-heat-recovery, and either on-site or off-site renewable energy will help the shift to the concept of net zero operational energy performance of data centers. Therefore, NZEB philosophy applied to digital infrastructure of high intensity translates into net-zero energy data centers.

Polyer et al. (2020) and Polyer et al. (2020) report on the concept of Net-Zero Energy Data Centers (NZEDCs) is premised on the principle of balancing the production of annual energy consumption with its on-site generation and mitigation of the environmental impact through the usage of renewable energy sources and operational reliability. To realize the performance of the NZEDC, there are two strategies which comprise cutting down the energy demands by means of energy saving systems coupled with renewable energy sources. Energy efficiency is done in combination with energy efficient design strategies that include building automation systems (BAS), installing high efficiency of HVAC equipment, lighting equipment and electrical equipment. Employing waste heat recovery, smart energy management systems, energy efficient information technology and heating ventilation systems contributes towards the net zero concept. ASHRAE standards - Compliance with the ASHRAE standards ensures the thermal and humidity environment around the IT equipment is kept within a reasonable range to minimize energy, so as to preserve reliability.

This research was aimed at selling the NZEDC idea. This paper introduces alternative cooling technologies that can be applied more differently to minimize the amount of energy consumed in the operation of a data center. It also considers setting up sophisticated HVAC optimization, integrating renewable energy, waste heat recovery choices and artificial intelligence-based energy controllers. The case study for this is a 100-kW data center in Arizona, USA, to demonstrate practical applications. The article assesses technical, operational, and regulatory issues and specifies research opportunities in the

future, such as lifecycle carbon accounting, standardization of sustainability measurements, and connectivity with the district energy network.

Literature Review

Net-zero data centers growth is caused by the increasing energy consumption and carbon footprint of digital infrastructure. The initial studies were mainly preoccupied with the better utilization rates of servers, which occur once the energy usage is decreased by means of incremental efficiency gains as opposed to systemic decarbonization. It encompasses inactive energy wastage, virtualization, consolidation of servers and combats high inherent idle IT equipment (computers, servers) (Jonathan Koomey. 2011). These further were augmented with the introduction of liquid cooling, hot- and cold-aisle containment, free cooling, which played a major role in minimizing overhead cooling energy and even allowed lower Power Usage Effectiveness (PUE) figures (Desmond Ondieki Ocharo, Agama Omachi). Although these measures produced quantifiable returns in efficiency, they focused heavily on increasing efficiency in the operations, though not overall energy consumption.

Research started to focus on real time data monitoring and intelligent energy management systems that are smart and efficient as efficiency was decreasing as close to the declining benefits as data centers were. PUE became a benchmark which allowed us to standardize and guarantee efficiency optimization on an industry wide scale (S. Greenberg et al, 2006). Other subsequent reports, however, criticized PUE as highly limited given that it overlooks the utilization of renewable energy, carbon intensity, and lifetime environmental impact (Shehabi, A., Smith, S.J., Hubbard, A., Newkirk, A., Lei, N., Siddik, M.A.B., Holecek, B., Koomey, J., Masanet, E., Sartor, D. 2024). Reactionary, task-based energy management systems were created in reaction, with the aim of automatically distributing work on the compute-units in response to energy availability and thermal state, to enable at least partial decoupling of performance and energy consumption (Fard, S. Y. Z., Sohrabi, M. K., Ghods, V., 2021). These strategies tended to experience suppository loads of labor, and they worked out well when managed in actuated settings and restricted their concept to time sensitive and important services.

The development next was based on the solar photovoltaic and wind renewable energy application in order to cover the remaining energy demand. Solar photovoltaics and wind power are on-site and off-site procurement solutions, such as power purchase agreements (M. Dayarathna, Y. Wen and R. Fan, 2016). Hybrid systems that involve electrical energy storage together with renewable systems were suggested to contain the irregularity and enhance reliability (D. Romanov, I. Chakraborty, S. Holler, 2025). According to recent investigations, energy balancing imbalances between energy production and renewable energy production have seen annual energy and emissions mismatches, which lead to a low reduction in emissions despite net-zero assertions (Shehabi, A., Smith, S.J., Hubbard, A., Newkirk, A., Lei, N., Siddik, M.A.B., Holecek, B., Koomey, J., Masanet, E., Sartor, D. 2024). This became a cardinal flaw of existing net-zero plans, which have been mostly biased towards financial compliance and not decarbonization of operations.

The availability of renewable energy sources is limited by the infrastructure and financial limitations to flexibility in integration. However, a small land supply and intense power needs are a major limitation to on-site generation of renewable energy to serve hyperscale data centers (M. Dayarathna, Y. Wen and R. Fan, 2016). High cost of capital, degradation, and environmental consequences, such as the extraction of materials and their subsequent disposal, and limit energy storage technologies. In more recent articles data centers are identified as participants in an integrated energy system, not consumers. The grid-support services offered by data centers can help to boost the use of renewable energy by using demand response, load shifting, and flexible scheduling (M. Dayarathna, Y. Wen and R. Fan, 2016). It is substantial conceptual progress, but a new operational complexity is being introduced, with cybersecurity threats, uncertainty-associated forecasting, and organizing with grid operators.

A few researchers suggested using waste heat to provide heating to districts and industries, thus increasing energy conservation. Waste heat recovery has become one of the strategies that seek to enhance the efficiency of the entire system of energy (D. Romanov, I. Chakraborty, S. Holler, 2025). Nonetheless, the actual implementation of waste heat recovery is restricted by low temperature conditions, lack of compatibility between sources of heat and demand, and the extra energy needed to upgrade technologies to improve heat. This makes waste heat recovery contingent and challenges to scale to a universal scale.

The optimization in cooling, workloads, energy storage, and integration of renewable energy available at the scale of the system is achievable because of improvements in artificial intelligence, digital twins, and predictive control systems (Fard, S. Y. Z., Sohrabi, M. K., Ghods, V., 2021). Combination of thermal, electrical and novel hydrogen-based energy storage are also referred to as important methods of long term decarbonization (D. Romanov, I. Chakraborty, S. Holler, 2025). Lastly, it is important that future studies should focus on creating holistic net-zero performance models that incorporate energy efficiency, carbon intensity, and lifecycle impact to make sure that net-zero data centers can have verifiable and sustained positive impacts on the environment.

The following few paragraphs give the latest development in the NZED journey. During the period between 2015 and 2018, the research was conducted to integrate renewable energy sources in the work of data centers. Her paper (Shehabi et al., 2016) researched practicability of solar photovoltaic (PV) systems and wind turbines to offset grid electricity, and past instances involved hybrid configurations wherein the renewable energy mixes with energy storage, which was less significant. To reduce grid dependency, the predictive workload scheduling aligns with availability of the renewable energy strategy. In-spite of these advances, challenges are pursued. Unpredictability in the amount of renewable energy generated caused temporal disparities between data center energy consumption and solar energy production. It had certain challenges such as expensive energy storage, challenging technology in retrofitting our existing facilities. In addition, the lack of consistency of performance in studies, restricting the adoption of net-zero practices in the industry.

Designed between 2019 and 2021, the very notion of Net Zero Energy Data Centers (NZEDCs) was formulated. According to Sengupta et al. (2021), NZEDCs are constituted by buildings that ensure parity between the annual energy use and the renewable energy generated on-site or off-site, with recycling the waste energy to the maximum (Sengupta, S., et al., 2021). The range of ambient air or water cooling is as free as possible and further development of individual cooling systems such as immersion cooling or liquid cooling became more commonplace during this period, pushing the PUE values. Concurrently, waste heat recovery strategies were investigated, such as district heating, thermal energy storage (TES), electricity generation based on the Organic Rankine Cycle (ORC) systems and heat pumps. These resolutions enhanced energy efficiency and energy sustainability. Yet, considerable limitations to real-world use were noted. The limited viability of renewable energy generation and the high cost and capital of the HVAC infrastructure, the mismatch with IT workloads and variable power supply, the greater complexity in operation, and regulatory restrictions were common barriers to using the waste heat.

Artificial intelligence the 2022–2023 research by NZED concentrated on an artificial intelligence-based energy management system, improved heat recovery methods and hybrid renewable integration. (Li et al., 2022) supported the fact that as much as 50 percent of the data center waste heat could be successfully reused using a combination of heat pumps and thermal energy storage (TES) (Li, X., et al, 2022). Zhang et al. (2023) suggested machine learning predictive models to plan the tasks with a parallel recent energy production so as to maximize energy usage and minimize grid reliance (Zhang, Y., et al., 2023). Regardless of this progress, the predictive models have certain limitations associated with them, as they require good and real time data, and errors in predictions emerge. Increased storage and infrastructure to contain, as well as operational issues such as keeping these technologies in equal usage with the older facilities. Moreover, the absence of standardized approaches to assessing net-zero performance will hinder the widespread use of this practice in the industry.

In all the research studies, the obstacles are alike. This consists of the lack of consistency in the IT energy demand and renewable energy production, measurement and standardization and high operational and capital costs. The intermittence in the generation of renewables solved the grid reliance problem and was poorly grappling with storage economics. Initial work on PUE enhanced efficiency of operations, however, they failed to sustain dependency on electricity derived out of fossil fuels. The waste heat recovery approach offered the availability of energy reuse but demanded further infrastructure. The recent AI-enhanced predictive schedules involve efficient data management systems, and it burdens operations.

Overall, the literature suggests that the research on data center sustainability has a definite trend of advancement and it has shifted as there is an increasing focus on efficiency-oriented PUE enhancements, followed by renewable integration, and, lastly, an intelligent energy metabolism with waste heat reuse. The progress in each phase served a technical purpose, but exposed enduring limitations, starting with economic considerations and time incompatibility, infrastructure needs, and standardization problems. These difficulties must be resolved to realize the movement of NZEDCs. The future of research will probably revolve around the effective ways of providing cost-effective energy

storage, the standardization of the net-zero performance measurements and the integrated AI-powered predictive energy management systems that can interface with urban energy networks to ensure the truly sustainable operations of data centers when they become low-carbon.

Methodology

Research Approach and Study Design

This paper will use a mixed-method research design that incorporates a systematic literature review and quantitative case study analysis. The literature review summaries of any research done on net-zero energy data centers concentrating on peer-reviewed sources and industry publications as well as ASHRAE and Lawrence Berkeley National Laboratory standards (Li, Q., Ma, R., Yang, M., Wang, W. and Chen, J., 2025). The case study element assesses a 100-kW embedded information center in Phoenix, Arizona with engineering computations in examining load analysis, renewable energy sizing and carbon emissions. This twofold strategy makes it possible to know the theory and verify the net-zero strategies in practice.

Case Study Selection Criteria

The data center was chosen based on 4 criteria that led to the 100-kW data center in Phoenix, Arizona. Solar irradiance is high in Arizona with values of 5.5 to 6.5 kWh/m²/day such that solar PV integration can be considered. Hot desert climate is a place which is extremely hard in cooling conditions thus it is a place where HVAC optimization strategies are put to the test. A 100-kW capacity is a typical small to medium scale data center size in which the findings are scalable (Alfadil, M.O., A. Kassem, M. and A. Al-Mansob, R., 2026). The availability of climate information, energy prices, and grid emissions indicators of Arizona allowed conducting accurate calculations.

Data Collection and Sources

The 2024 United States Data Center Energy Usage Report based on the 2024 data on energy consumption in the United States and carbon emission estimates of the country respectively have been utilized as primary data in this work. Peer-reviewed articles were written on the topic of PUE optimization, renewable integration, and waste heat recovery, which made up secondary data. We took climate information about Phoenix through the national renewable energy laboratory solar irradiance database (Bedi, A., Ramprabhakar, J., Anand, R., Meena, V.P. and Hameed, I.A., 2025). Values of equipment efficiency based on COP and PUE baselines were calculated using the ASHRAE standards and industry's best practice guides.

Calculation Methods and Tools

Microsoft Excel was used to calculate all the information. Power Usage Effectiveness was determined as the total facility power/IT equipment power. The annual energy consumption was calculated by multiplying total load in kilowatts by 24 hours daily and 365 days. PV system sizing was conducted based on the formula of necessary annual energy kilowatt hours divided by annual production of solar energy with each kilowatt which is 1,800 kilowatt hours per year at Phoenix. The computation of battery storage capacity was done according to total load x 4 hours of preferred backup hours (Bera, M., Das, S., Garai, S., Dutta, S., Choudhury, M.R., Tripathi, S. and Chatterjee, G., 2025). The grid factor was 0.4 kilograms CO₂ per kilowatt hour carbon emissions. Waste heat recovery assumed half of the IT load was recoverable.

Performance Metrics and Evaluation Framework

This study used three performance measures. Power Usage Effectiveness is a measure of energy performance between IT and facility loads with 1.3 being the optimization objective. Carbon Usage Effectiveness measures CO₂ emission per kilowatt hour of IT loads simplified in this research as total emissions in this paper (Chountalas, P.T., Chrysikopoulos, S.K., Agoraki, K.K. and Chatzifoti, N., 2025). The energy balance net-zero condition directs that the yearly on-site renewable generation corresponds to and must be higher than the yearly facility consumption. Power Usage Effectiveness of less than 1.3 or equal, 100 percent offset power renewable, and zero net operation carbon emissions are criteria of success.

Assumptions and Limitations

This study has several assumptions. There is no change in load at either extreme of Working load or therefore the IT load is constant at 100 kilowatts. Solar generation with consideration to annual means without regard to days and seasons. Batteries can only be used to offer backup and not load shifting. The 0.4 kilograms of CO₂/ kilowatt hour is a grid emissions factor average in Arizona. Cooling coefficient of performance [26]. Shortcomings are the absence of operational data in real time, simplified analysis of waste heat recovery, and omission of embodied carbon of construction and manufacturing of hardware. Results are theoretical upper limits of performance and not real operational data.

Data Center Energy Analysis

Baseline Energy Consumption Analysis

The analysis of baseline energy consumption provides the reference point to any optimization action to be taken. The IT load of the data center is 100 kW. The initial Power Usage Effectiveness is 1.5, and the total facility load is 150 kW (including cooling, power distribution and auxiliary systems) so the IT equipment requires extra cooling, power distribution and auxiliary systems which consume 50 kW. The

annual energy consumption of the IT (Table-1) is 876000 Watt/year, and the total facility energy consumption is 1314000 Watt/year operating 8760 hours per year. This benchmark indicates that the non-IT loads take up about 438,000 kWh/year, which is 33 percent of the total energy consumption. The main source of this overhead, and which is consistent with literature, is the cooling systems, which consume most of the energy after the IT equipment (Gassar, A.A.A. and Jafar, R., 2025). This is the point of reference used to consider all the optimization strategies that follow.

Table 1
Baseline Energy Consumption Analysis

Parameter	Value	Unit
IT Load	100	kW
Initial PUE	1.5	-
Total Facility Load	150	kW
Hours per Year	8760	hours
Annual IT Energy Consumption	876000	kWh/year
Annual Total Energy Consumption	1314000	kWh/year
Initial PUE	1.5	-
Total Facility Load	150	kW

Cooling System Optimization Analysis

The cooling system optimization analysis is an evaluation of the energy savings that can be attained through enhancement of coefficient of performance (Table 2). Because the desert of Phoenix is in a hot climate, cooling load is estimated at 120 percent of the IT load or at 120 kW. The initial COP of 3 means the required cooling power of 40 kW. Once the high-efficiency chillers and liquid cooling methods are used to optimize it, the COP can be improved to 4.5, which decreases cooling power to 26.67 kW. The output of this optimization is cooling power savings of 13.33 kW, indicating a 33.33 percent reduction in cooling energy consumption (Mavisclara, O.A., Oshobugie, I.I., Olufunmi, A.T., Bolaji, A.A., Olawale, A.O., Anulika, N.C. and Kenechukwu, O., 2025). The savings directly add towards reducing the overall facility load as well as increasing the overall Power Usage Effectiveness. The analysis shows that modernizing the cooling equipment is an effective approach to cut down on energy use at data centers.

Table 2
Baseline Energy Consumption Analysis

Parameter	Value	Unit
IT Load	100	kW
Cooling Load (120% of IT Load)	120	kW
Initial COP	3	-
Initial Cooling Power	40	kW
Optimized COP	4.5	-
Optimized Cooling Power	26.67	kW
Cooling Power Savings	13.33	kW
Savings Percentage	33.33	%

Power Usage Effectiveness (PUE) Improvement Analysis

The analysis of Power Usage Effectiveness improvement (Table 3) also measures energy savings, which are an improvement of PUE of 1.5 to 1.3. With a fixed IT power need of 100 kW, the initial total power need of the facility is 150 kW, and the optimized total need is 130 kW with load decrease of 20 kW. The first-year energy consumption was 1,314,000 kWh/year and the energy consumption was optimized at 1,138,800 kWh/year with 8760 hours of operation in a year. The cumulative end year saving of energy (in kWh/per year) is 175200, which expresses a 13.33 percent decrease as compared to the previous year. This maxim directly lowers overhead in cooling and distribution of power (Burato, M., 2025). A PUE of 1.3 makes this facility one of the most efficient data centers, to a significant extent minimizing the required renewable power to operate with zero net effect.

Table 3
Power Usage Effectiveness (PUE) Improvement
Analysis

Parameter	Value	Unit
IT Load	100	kW
Initial PUE	1.5	-
Optimized PUE	1.3	-
PUE Reduction	0.2	-
Initial Total Load	150	kW
Optimized Total Load	130	kW
Load Reduction	20	kW
Initial Annual Energy	1,314,000	kWh/year
Optimized Annual Energy	1,138,800	kWh/year
Annual Energy Savings	175,200	kWh/year
Savings Percentage	13.33	%

Renewable Energy Sizing Analysis

The net-zero energy operation is achieved by determining the amount of solar PV capacity (Table 4) that would be needed to operate in a net-zero environment. Having an optimization of total load of 130kW, and annual energy demand = 1,138,800kWh/per year, the plant should be capable of producing this quantity by utilizing on-site solar PV. Phoenix has high solar irradiance that produces 1800kwh of electricity per kilowatt of the PV mounted. As such the necessary PV power is 633 kW. This installation would require an estimated area of 4,112 square meters on the rooftop (Islam, M.S. and Sabiruzzaman, M., 2025). This discussion affirms the fact that a net-zero operation can be practically attained with the help of solar PV integration. But land area requirement can be higher than there is rooftop area implying the introduction of ground-mounted or carport-mounted arrays to obtain renewable energy capacity to sustain the entire load.

Table 4
Renewable Energy Sizing Analysis

Parameter	Value	Unit
IT Load	100	kW
Optimized PUE	1.3	-
Optimized Total Load	130	kW
Hours per Year	8760	hours
Annual Energy Required for Net-Zero	1,138,800	kWh/year
Solar Generation per kW PV (Phoenix)	1800	kWh/kW/year
Required PV Capacity	633	kW
Estimated Rooftop Area Required	4112	m ²

Battery Storage Requirement Analysis

The analysis of battery storage (Table 5) allows identifying the four-hour backup capacity required in case of continuous operation in the case of grid failures. This means that its total facility power of 150 kW (including all power utilization in the facility) will need a battery capacity of 600 kWh. The usable capacity becomes 667 kWh, or the result of 90 round trip efficiency. The battery capacity that will be needed is 13,889 Ah at a system voltage of 48 volts. The amount of commercial battery units required is about 49.4 using commercial battery units with a capacity of 13.5 kWh/unit (Kadir, N. and Fung, A.S., 2025). The storage system will provide constant utilization of data centers when there are brief interruptions with the grid and will also assist with utility of renewable energy as it will store the oversupply of solar production. Nevertheless, the huge investment in capital of 50 battery units constitutes a big cost that needs to be factored in net-zero economic feasibility studies.

Table 5
Battery Storage Requirement Analysis

Parameter	Value	Unit
IT Load	100	kW
Initial PUE	1.5	-
Optimized PUE	1.3	-
PUE Reduction	0.2	-
Initial Total Load	150	kW
Optimized Total Load	130	kW
Load Reduction	20	kW
Initial Annual Energy	1,314,000	kWh/year
Optimized Annual Energy	1,138,800	kWh/year
Annual Energy Savings	175,200	kWh/year
Savings Percentage	13.33	%

Waste Heat Recovery Potential Analysis

The waste heat recovery analysis (Table 6) estimates the possibility to reuse heat produced by the IT equipment. The facility recovers 50 kW of waste heat with a recoverable heat at 50 percent of the IT load. Annually this amounts to 438,000 kWh of recoverable energy. The useful heating output becomes 1,533,000 kWh per year with the help of a heat pump with the coefficient of performance of 3.5. This can satisfy the heating requirement of about 153 average households monthly. Moreover, switching to natural gas heating to recover waste heat removes 613 200 kg of CO₂ per year (Khara, S., Soni, S., Pandit, B., Chauhan, V., Patel, A., Kumar, R. and Bhatt, V., 2026). Phoenix, however, has mild winters which constrain the demand for heating by local districts. Thus, waste heat recovery is more feasible in colder climates where heating is required all year round.

Results

Table 6
Waste Heat Recovery Potential Analysis

Parameter	Value	Unit
IT Load	100	kW
Recoverable Heat Percentage	50	%
Recoverable Heat	50	kW
Hours per Year	8760	hours
Annual Recoverable Energy	438,000	kWh/year
Heat Pump COP	3.5	-
Useful Heating Output	1,533,000	kWh/year
Average Home Heating Demand	10000	kWh/year/home
Equivalent Homes Heated	153.3	homes
CO2 Offset (vs Natural Gas)	613,200	kg CO2/year

Carbon Emission Reduction Analysis

The emission of carbon reduction analysis (Table 7.1) measures the benefit of the environment (Table 7.2) to an improvement of PUE between 1.5 and 1.3. The 1,314,000 kWh of energy used the first year leads to 525,600 kg of CO₂ emissions, given the grid factor of 0.4kg CO₂/kWh. Following optimization, yearly energy use is cut down to 1,138,800 kWh which translates into 455,520 kg of CO₂ (Zei, S., Rrci, M. and Al-Khalidi, A., 2025). The overall CO₂ saved (by means of energy savings) is 70080 kg per year that corresponds to a 13.33 percent saving. The decrease can be compared to elimination of 15.2 vehicles every year or plantation of 3,185 trees every year. The emissions would be reduced to zero under full net-zero operation with on-site renewable energy which would be a zero-carbon footprint.

Table 7.1
Carbon Emission Reduction Analysis

Parameter	Value	Unit
IT Load	100	kW
Initial PUE	1.5	-
Optimized PUE	1.3	-
Initial Annual Energy	1,314,000	kWh/year
Optimized Annual Energy	1,138,800	kWh/year
Grid Emissions Factor	0.4	kg CO2/kWh
Initial CO2 Emissions	525,600	kg CO2/year
Optimized CO2 Emissions	455,520	kg CO2/year
Total CO2 Reduction	70,080	kg CO2/year
Reduction Percentage	13.33	%

Table 7.2
Environmental Equivalence

Parameter	Value	Unit
Equivalent Cars Removed from Road	15.2	cars/year
Equivalent Trees Planted	3185	trees/year

Results

Summary of Energy Efficiency Improvements

Analysis of energy efficiency showed that optimization of cooling and a decrease in PUE was achieved significantly. The initial PUE of 1.5 giving a total facility load of 150 kW and an annual energy usage of 1,314,000 kWh was achieved by the establishment of the baseline assessment, which set up an IT load of 100 kW. The optimization of the cooling system, which decreased the cooling power by 13.33 kW to 26.67 kW, had the effect of increasing the coefficient of performance by 3.0 to 4.5 and included a cooling power savings of 13.33 kW which is equivalent to 33.33 percent. The increase in PUE of 1.5 to 1.3 decreased overall load of the facility to 130 kW and annual electricity usage to 1,138,800 kWh. All these energy efficiency actions result in a yearly energy savings of 175,200 kWh which is a 13.33 percent cut. Such savings cut directly the amount of renewable energy needed to facilitate net-zero operation.

Renewable Energy and Storage Requirements

The analysis of renewable energy calculated the solar PV capacity and battery storage needed to operate the system net-zero. The PV capacity of 633 kW is calculated based on the optimized annual energy consumption of 1,138,800 kWh/year and the solar generation potential in Phoenix that is 1800 kWh/kW/year. The approximate size of the rooftop required to install this is 4,112 square meters that might be less than the size of the rooftop available hence carport established on the ground or rooftop arrays may be considered (Tsegaye, S., Heyi, K.G., Endaylalu, M.T., Melaku, Z.A. and Turufi, K.T., 2025). The four-hours of grid outage battery storage analysis showed that the necessary capacity is 600 kWh. When the round-trip efficiency is taken into consideration (90 percent), the usable capacity is 667 kWh. With commercial battery units of 13.5 kWh capacity, it will take a bit over 49.4 units to maintain continuous operation when the grid goes dead.

Environmental Impact Summary

The carbon reduction benefits quantified in the analysis of the environment through efficiency improvement and waste heat recovery. The starting CO₂ emissions were 525,600 kg /yr based on the grid factor of 0.4 kg/kWh. With the following optimization of PUE to 1.3, emissions went down to 455,520 kg per year which comprised a cut of 70,080 kg per year which translated into 13.33 percent. This cutting is equivalent to taking 15.2 cars off the road per year or planting 3,185 trees per year. The waste heat recovery analysis indicated that 50 percent of the IT load or 50 kW can be recovered, and it equals 438,000 kWh per year. The useful heating output can be 1,533,000 kWh/year with a COP of 3.5 enough to heat 153 average homes. By substituting natural gas heating with recovered waste heat an extra 613,200 kg of CO₂ emissions will be eliminated each year.

Comparative Analysis of Key Metrics

The comparative analysis shows before and after optimization metrics to display an overall performance improvement. The table below presents the main changes which are realized due to cooling optimization and reducing PUE. The comparison (Table 8) illustrates that solely improved efficiency will decrease energy use and emissions by more than 13 percent. The highest percentage point of 33.33 percent is at cooling optimization. With a full net-zero where it is operated with on-site solar PV, CO₂ emissions would be removed, creating zero operational carbon footprint.

Table 8
Comparative Analysis of Key Metrics

Parameter	Before Optimization	After Optimization	Reduction
PUE	1.5	1.3	13.33%
Total Facility Load (kW)	150	130	13.33%
Annual Energy (kWh/year)	1,314,000	1,138,800	13.33%
Cooling Power (kW)	40	26.67	33.33%
CO ₂ Emissions (kg/year)	525,600	455,520	13.33%

Key Findings Summary

The key results of the full analysis of the 100-kW data center in Phoenix, Arizona are as follows. To begin with, a decrease of PUE (1.5 to 1.3) saves the energy used on a daily basis by 175,200 kWh which translates to a saving of 13.33 percent per year. Second, COP can be optimized with cooling systems to minimize cooling power by 33.33 percent, decreasing the mean of 3.0 to 4.5. Third, completing the net-zero operation needs 633 kW of PV solar capacity, but this would take up about 4,112 square meters of terrestrial land or rooftop. Fourth, 600 kWh capacity is only equivalent to 49.4 units of commercial batteries (four-hour battery backup) (Ahmad, H., Yaqub, M. and Lee, S.H., 2025). Fifth, the waste heat recovery can benefit 153 households and compensate for 613,200 kg of CO₂ per year. Sixth, CO₂ emissions are minimized by 70,800 kg/per year (equivalent) to 15.2 cars off the road due to the parameters in efficiency measures only.

Discussion

Interpretation of Energy Efficiency Results

The obtained energy efficiency outcomes prove that optimization of the cooling system and PUE minimization are two effective measures that can help to reduce energy consumption in data centers. The saving of 33.33 percent, that is, the difference between the cooling power of 40 kW against 26.67 kW, because of increasing COP, is evident in the improved COP of 4.5 against 3.0. This is an outcome that is practically meaningful due to the fact that cooling systems normally constitute half of the non-IT energy use. The gain of 1.5 to 1.3 in the PUE decreased the total facility load by 20 kW, as well as the annual energy use by 175,200 kWh. This degree of PUE makes the facility one of the most efficient data centers that are on par with the best-in-class hyperscale facilities. Nevertheless, to have PUE below 1.3, more investments in liquid cooling or free cooling systems would have to be applied. The findings affirm that energy efficiency needs to be of the foremost importance before implementing renewable energy in order to reduce the amount of PV capacity and storage expenses needed.

Implications for Net-Zero Data Center Design

The findings are important to the future data center design in a number of ways. To start with, the choice of location has a huge influence on net-zero feasibility. Depending on the weather, Phoenix has high solar irradiance resulting in the feasibility of solar PV, however, hot climates increase cooling loads. Major focus on locations where there is both renewable energy potential and moderate climates should be taken so the designers minimize the cooling needs (Elliot, J., Brown, J., Mlilo, N. and Bowtell, L., 2025). Second, it is essential to choose a cooling system. The 3.0 to 4.5 increment in COP indicates that the returns of investing in high-efficiency chillers or liquid cooling are high. Third, actual solar variability has to be considered when sizing PV capacity. The 633 kW PV size can only occupy 4,112 square meters, which would not be feasible in small locations. On site generation may not be adequate and designers

should look at off-site renewable procurement or power purchase agreements. Fourth, grid independence battery storage is still costly, and hybrid grid-connection designs are more viable today.

Practical Challenges and Implementation Barriers

The obtained energy efficiency outcomes prove that optimization of the cooling system and PUE minimization are two effective measures that can help to reduce energy consumption in data centers. The saving of 33.33 percent, that is, the difference between the cooling power of 40 kW against 26.67 kW, because of increasing COP, is evident in the improved COP of 4.5 against 3.0. This is an outcome that is practically meaningful due to the fact that cooling systems normally constitute half of the non-IT energy use. The gain of 1.5 to 1.3 in the PUE decreased the total facility load by 20 kW, as well as the annual energy use of 175,200.

Interpretation of Energy Efficiency Results

The net-zero energy data centers have several practical challenges that restrict their use. The major obstacle is high capital costs. The 633-kW solar, 600 kWh battery storage and highly developed cooling facilities cost a lot of money, which might not be affordable to small to medium businesses. The other limitation is the availability of land. The space required to install PV ground-mounted is 4,112 square meters that might not be available in urban areas where many data centers are located. Operational problems are posed due to solar intermittency. The calculation was based on average generation per annum, yet in reality, production is daily and seasonal making PV to be over-sized or more storage is needed. Waste heat recovery is limited in hot climates such as in Phoenix where demand for district heating is low. Lastly, regulatory obstacles such as building regulations, grid connections, and permitting procedures may slow down or halt net-zero applications.

Limitations of the Study

There are several limitations to this study which need to be noted. The analysis takes IT load constant at 100 kW of no workload changes, contrary to the real-world scenarios where in most cases server utilization changes widely. Annual values of 1,800 kWh per kilowatt per year were used to measure solar generation, neglecting daily, seasonal and weather variations which influence the actual production. The battery storage was only expected to be used on a backup scale but not on the daily load shifting or smoothing renewable, which would be at a larger scale. The grid emissions factor (0.4 kg CO₂ per kWh) is the Arizona average but fails to account for Hourly changes in grid carbon intensity. Construction material (embodied carbon) was not counted. Production of IT devices and batteries was not counted. Waste heat recovery used 50 percent of recoverable heat but ignored the losses due to distribution and the cost of infrastructure. Results are theoretical values of maximum performance and not actual operating figures.

Recommendations for Practice

Depending on the results, it presents a number of recommendations to data center operators and designers. First, make some energy efficiency improvements that can be realized first before investing in renewable energy. By lowering PUE by 0.2 to PU 1.3, it lowers the PV capacity requirements at 97kW and battery storage needs at 60kWh, thus dramatically reducing startup costs. Second, perform site-specific solar resource assessment based on past data and not annual averages to take seasonal variations into consideration. Third, think of options other than grid independence: hybrid grid connected. The grid connection minimizes the battery storage and gives reliability during low-solar prolonged periods. Fourth, learn more about waste heat recovery in warm climates, by identifying local industrial applications with 24-hour heating requirements like laundry or greenhouses. Fifth, carbon accounting of lifecycles in net-zero planning to tackle embodied emissions. Sixth, communicate early with utilities on the requirements of interconnection, and availability of demand response programs that will help offset costs of storage.

Conclusion

This paper is a thorough examination of Net-Zero Energy Data center (NZEDC) strategies and provides a more detailed case study of a 100-kW center in Phoenix. Key findings include.

1. Feasibility of Net-Zero Operation: The 100-kW data center can also be configured with net-zero energy consumption with the aid of integration of renewable energy (solar PV), energy-efficient HVAC systems, AI-driven workload management, and waste heat recovery without compromising its operational reliability.
2. Energy Efficiency Gains: The use of cooling and IT infrastructure optimality minimized Power Usage Effectiveness (PUE) by 1.5 to 1.3 which translated to a yearly energy saving of about 175200 kWh (13.3%).
3. Carbon Emission Reduction: By integrating to 100 percent renewable energy in the facility, the facility will be able to reduce about 455,500 kg/CO₂ greenhouse gas emissions annually, which is an opportunity to prove the environmental impact potential of NZEDCs.
4. Challenges: Although technically viable, high capital cost, land area to install PV arrays, intermittency arising in renewable utilization and restricted applicability of waste heat in hot climates, cripple practical implementation.
5. Future Directions: Implementation of hybrid energy infrastructure, predictive AI energy management and standardized performance measurements are essential to scalable, cost effective NZEDC application. Sustainability can be further boosted with lifecycle carbon accounting and integration with the city energy networks.

NZEDCs are a feasible solution to achieving sustainable digital infrastructure, as they entail tech innovation, green energy, and smart work procedures. In the 100-kW case study, it is clear that even with proper planning, a net-zero-energy operation can be attained, and this can serve as a scalable example of creating a data center that is environmentally responsible.

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Figures

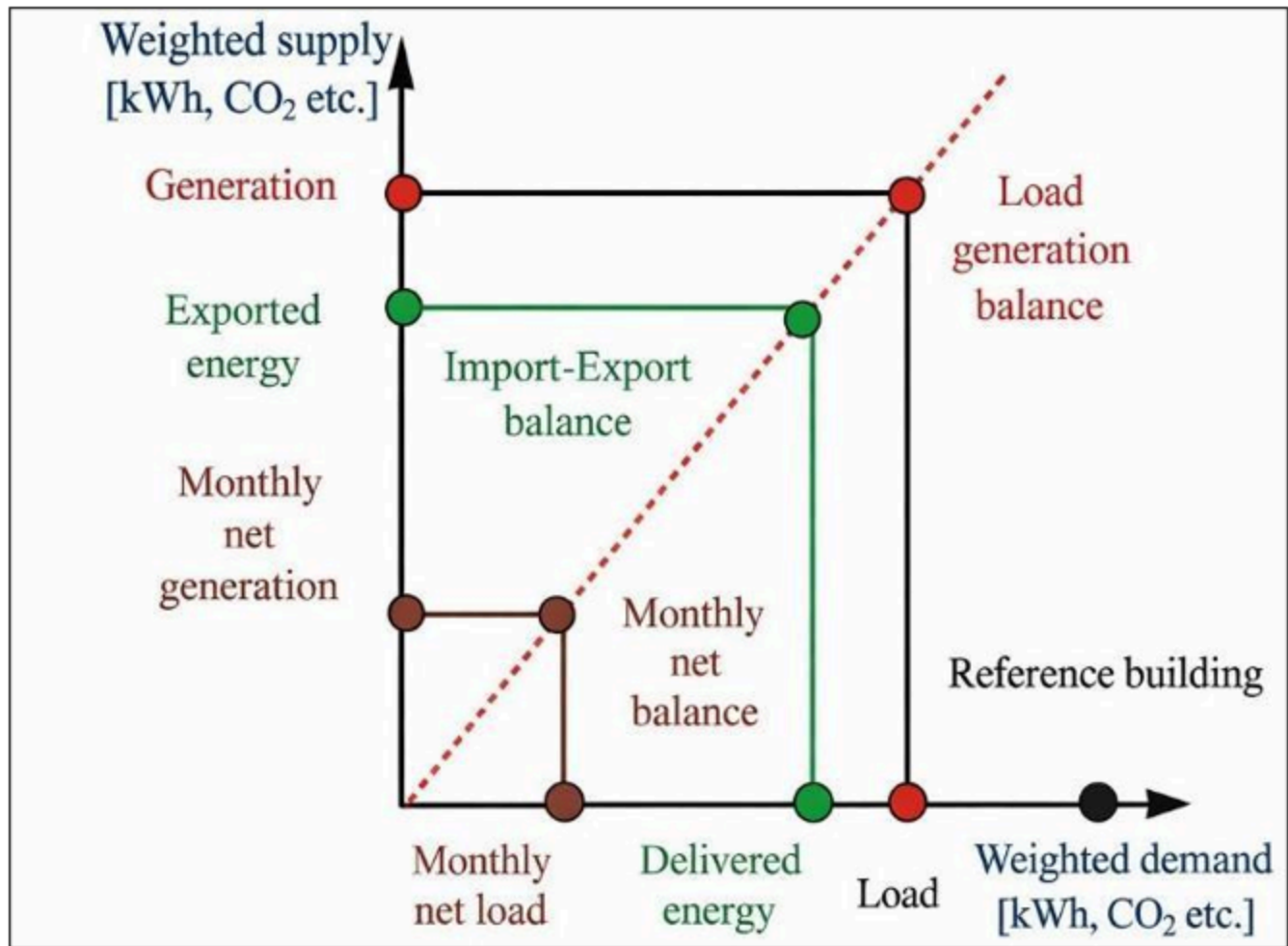


Figure 1

Graphical Representation of NZEB

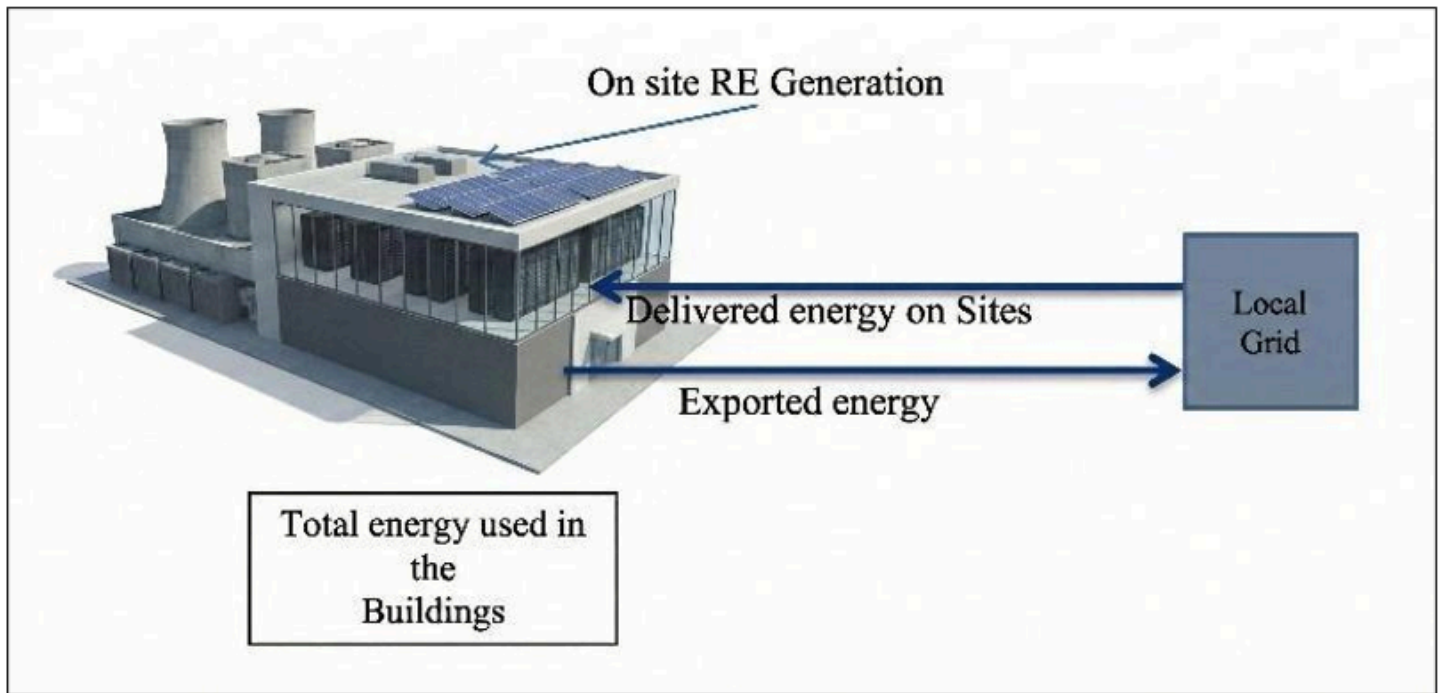


Figure 2

Net Zero Data Center Concept. (Source: <https://energy.prayaspune.org>)