Accelerating data center decarbonization and maximizing renewable usage with grid edge solutions

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***Abstract*— Data centers and other computing clusters have unique electrical power requirements. They demand high reliability with high power quality, while at the same time are being driven by society and industry to use renewables as their only electricity source. To date, many large data center users have focused on offsite renewable portfolio contracts and power purchases agreements to offset data center energy demands. However, this strategy misses several greenhouse gas contributors: the diesel and gas generators that provide back-up, and the reliance on existing fossil fuel generation that often balances renewable output power in utility networks. With grid edge solutions including microgrids, fuel cells, and battery energy storage systems, data centers have an opportunity to maximize their usage of renewable generation while minimizing the usage of fossil-driven energy generation.**

This paper explores the key considerations for using grid edge technologies to decarbonize the back-up supplies for data centers, as well as explore how they can stabilize the utility networks that supply data centers--even as the penetration of renewable generation in the network reach 100%. We will introduce the strategies implementation, including an overview of the design, management, control, and optimization of their renewable energy supply. We will explore the economic considerations for these investments, while providing useful benchmarks for achievable goals in each of these areas.

Keywords—grid edge solution, microgrid, data center, renewable, decarbonization, back-up

I. INTRODUCTION

Data centers are becoming more and more integrated to modern life providing services from website hosting, financial services, and forecast models. Data center and cloud services are being used much more due to COVID-19 pandemic that created new norm for online services. Data centers are projected to account for 3.5% of total electricity demand globally in near future [1].

Giant tech companies providing cloud services having data centers, introduced their initiatives towards a carbon free and renewable path. Microsoft announced to go carbon negative by 2030 and remove all carbon the company has emitted since it was founded in 1975 by 2040 [2]. Google has been carbon neutral for over a decade and matched 100% of their global electricity consumption with renewable energy with the end goal of having its data centers to be 24x7 carbon free [3]. Amazon is committed to powering its operations with 100% renewable energy by 2025 as part of the goal to reach net zero carbon by 2040 [4]. Facebook's global operations will achieve net zero greenhouse gas emissions and be 100% supported by renewable energy [5].

These goals illustrate a general trend of technology firms to increase the use of renewable energy and offset energy usage with power purchase agreements. However, these data centers still rely on networks that include non-renewable and fossil-based generation. Hence, these companies lean heavily on a tool known as a renewable energy credit (REC), which is a token for a utility's green energy generation. RECs are how companies like Google and Microsoft can claim their data centers are supplied 100% by renewables while still being connected to grids that use fossil fuels. The more ambitious goal announced by Google is to power data centers by renewables in hourly basis.

The second issue is related to the need for high reliability power source for Data centers. This is achieved by using back-up generators during power outages that are fueled by diesel or gas as another carbon footprint. However, there is interest in increasing the use of renewable energy for back-up. For example, Microsoft has announced targets specifically "aiming to eliminate … dependency on diesel fuel by 2030." [6]. These two issues will bring microgrids to the play for carbon-free data centers.

As defined by CIGRE Working Group C6.22, "microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded." [7]

Microgrids manage a variety of energy sources to meet environmental goals as well as resiliency needs with smart control and automation systems. In this paper we will evaluate the combination of hydrogen, renewables, and energy storage technologies for a data center. The benefits of decarbonizing the backup power with the coming challenges including efficiency and required area will be discussed in the next sections.

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II. DATA CENTER BACK-UP INFRASTRUCTURE

Traditional back-up power supplies for data centers include a combination of short-term power back-up from Uninterruptible Power Supplies (UPS) usually battery based and longer-term back-up from reciprocating engines that operate on gas, if available, and, more broadly, diesel fuel. Two promising technologies for data center back-up are battery energy storage systems (BESS) and fuel cells.

BESS, similar to UPS, use batteries for storing energy, however they connect to the network differently. UPS sit in series with the loads and provide short-term reliability to devices connected downstream. BESS, in contrast, are connected in parallel to the network, which enables them to inject power and provide services that support the data center in both the upstream network and the downstream infrastructure. This architecture allows the data center to host significant renewables while improving network stability. During utility outages, it also allows the data center to reduce the usage of back-up fuel and improve their operating efficiency.

Fuel cells use catalytic reactions to convert input fuel into electricity, and sometimes heat. Fuel cells which use hydrogen produced via water electrolysis powered by renewable electricity, can be used as an alternative clean back-up power supplies in data centers. Microsoft plans to replace all diesel generators at their Azure datacenters with hydrogen powered fuel cells by 2030 [8].

Hydrogen can be produced locally by electrolyzers combined with onsite renewables or powered by renewable electricity imported via a utility grid. Alternatively, green hydrogen can be produced remotely in large quantities and delivered to a data center by trucks. A certain minimum amount of hydrogen must be stored locally to guarantee a required level of autonomy. Recently a 250 kW fuel cell system, was able to power 10 server racks for 48 hours by generating 12 MWh of electric energy in Microsoft data center in Utah, USA. Assuming a typical energy density of hydrogen as 33 kWh/kg and conversion efficiency of fuel cell of 50%, 730 kg of hydrogen are required to generate 12 MWh (c.f Figure 1). The new company target is to replace 3 MW back-up diesel generators by using fuel cells powered by green hydrogen at the same site.

Figure 1. Compressed hydrogen stored in tanks as a fuel for back-up fuel cells in Microsoft Salt Lake City data center [8]

Various combinations of these technologies determine the "tier" of the architecture, which defines the reliability level of the data center's power supply [9], [10]. Without strictly defining tiers, "tier 1" - "tier 4", are currently observed in an ascending order of redundancy.

Tier 1 architecture is the simplest. It is also called as N design concept, because "N" information technology (IT) loads need "N" sets of UPS units and gensets. A degree of redundancy is achieved via tier 2, or N+1 topology, due to the additional UPS and genset installation respectively. Tier 3 has a double delivery path; an active path with a UPS and a passive path without a UPS. Lastly, tier 4, being the most reliable topology has two active feeders with a redundant UPS and genset in each feeder as shown in Figure 2.

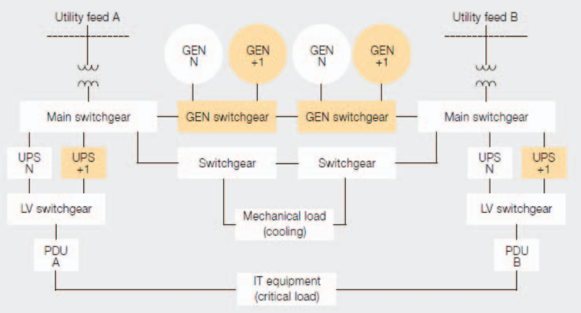

Figure 2. Tier 4 Data center design principle [11]

The base characteristics that differentiate the tiers are summarized in Table 1. The downtime of tier 4 data center is almost 70 times less compared to tier 1. Moreover, the minimum number of hours of autonomous, isolated operation capability is provided for tiers 3 and 4.

Table 1. Differentiation metrics between tiers architectures [9, 10]

	Tier 1	Tier 2	Tier 3	Tier 4
Paths	1	1	1 active 1 passive	2 active
Redundancy	N	N+1	N+1	2(N+1)
Utility voltage [kV]	< 0.48	< 0.48	12-15	12-15
Annual IT downtime [h]	< 8.8	< 22	< 1.6	< 0.4
Power outage protection [h]	-	-	> 72	> 96
Availability [%]	> 99.671	> 99.749	> 99.982	> 99.995

III. DATA CENTER POWER AND ENERGY NEEDS

As shown in Figure 3, the majority of data center loads across the globe are either less than 2 MW or greater than 30 MW [11].

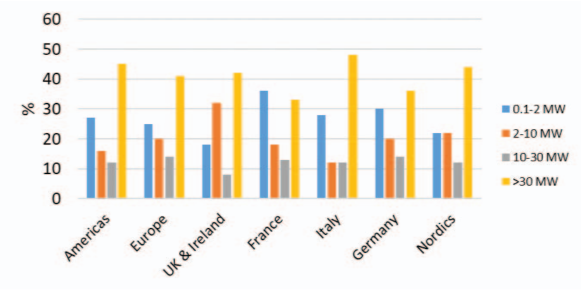

Figure 3. Spread of data center loads by region

Below we estimate the back-up supply system energy needs for a tier 4 data center with a constant load of 30 MW and uninterruptable operation for 100 hours. Different energy sources, i.e. BESS, fuel cells and diesel gensets are examined. The total energy need for this back-up scenario is 3000 MWh.

A typical diesel genset is able to generate 3 kWh per liter of diesel fuel. Therefore, one million liters of fuel must be stored on-site, as illustrated in Table 2.

Table 2. Energy requirements for 100-hours back-up protection.

Data center demand, MW	Required battery size (90% round trip efficiency), MWh	Required amount of hydrogen (50% fuel cell efficiency), tons	Required amount of diesel fuel, liters
2	220	12	65000
30	3300	180	1000000

Diesel fuel in Europe is typically transported by trucks that can carry up to 40000 liters, thus about 25 trucks are needed to deliver the required amount of fuel for 30 MW data center back up supply [12].

The amount of hydrogen needed to generate 3000 MWh is about 180 tons. Hydrogen tanks may accommodate 23 kg/m^3 at 350 bars and 38 kg/m^3 at 700 bars resulting in a required tank size of 4800 – 7900 m^3 [13]. A large truck can deliver up to 1 tonne of hydrogen at 700 bars [14] therefore without a microgrid that enables local generation to generate local hydrogen, it could require up to 200 trucks to deliver the required amount of hydrogen.

Typical power densities can vary between 0.5–11 kW/m^2 with the higher values associated to the latest IT technologies [15]. The large differences are due to equipment thermal capabilities and the cooling methods applied in the facility. Availability of land also affects selected power density (i.e. urban vs rural areas).

We assume a data center located Europe area and has an average power density of 5 kW/m^2, so a large 30 MW data center would have a 6000 m^2 roof surface available for solar photovoltaic (PV) installation. A small 2 MW data center would have a 400 m^2 rooftop. Peak solar panel efficiencies range between 16% and 45% [16]. These area efficiencies apply to the AM1.5 global spectrum as a standard, which has irradiance of 1 kW/m^2 [17]. Factoring in likely efficiency, with standard radiation, and based on expected commercial availability, together with effective spacing required between panels, we assume a net area efficiency of 0.14 kW$_p$/m^2. The 30 MW data center roof can host about 840 kW$_p$ of solar PV. The smaller 2MW data center rooftop could host 56 kW$_p$. The expected solar production by location, either Nordic Europe (e.g. Sweden) and South Europe (e.g. Spain) is summarized in Table 3.

Table 3. Solar PV production summary.

Data center demand, MW	Rooftop space, m^2	Rooftop PV hosting capacity, kW$_p$	PV energy in 100 hours, MWh	
			Nordic	South
2	400	56	0.62	1.1
30	6000	840	9.2	16

The table shows that the location of the data affects the available solar energy. The Nordic plants would be more impacted by the space limitations for producing enough solar energy, and particularly if the outage would happen during the extended winter period. We note that, if available, the abundant hydroelectric systems could alleviate this issue but are not evaluated here since they are very site specific. In contrast, southern locations have more consistent daily solar patterns throughout the year.

If fuel cells are deployed and hydrogen is produced via water electrolysis for a year to prepare for the outage, then about 64,000 m^2 of solar PV panels would be needed to produce a required amount of hydrogen. Even storing up the hydrogen for a year, this is about 10 times more the available roof-top space of data center. The installed power capacity of the solar PV plant is about 9 MW$_p$ with electrolyzer around 9 MW.

A hypothetical scenario with solar PV charging a an unrealistically large 3300 MWh Li-ion BESS for a year, about 25,000 m^2 of solar PV panels are needed to produce the required electrical energy to charge the BESS to provide all back-up. The solar PV capacity would be around 3.5 MW$_p$. If we factor in a battery self-discharge of 2% per month, then the effective battery round-tip efficiency drops from 90% to 71%. In this case, 32,000 m^2 solar PV are required for solar PV capacity of around 4.7 MW$_p$.

These analyses demonstrate the challenge of solutions that only focus on on-site green hydrogen, or a simplistic BESS strategy. Both required large solar PV plants exceeding available roof surface. A strategy to go 100% renewable should factor this into the planning.

Another challenge with solar for back-up is that most solar PV installations globally use grid-following inverters and must be connected to a stable grid. During normal operations the electric network utility provides this service. However, during utility outages when the data center is in back-up operation, grid edge solutions (GES) are necessary for solar to generate. The GES enables the PV to operate with grid-forming technologies, including appropriately configured back-up generators and/or BESS. Depending on the plant location (e.g. urban facilities), hydrogen refilling via dedicated trucks or pipelines could be a supplement solution.

IV. PURSUING 100% CARBON-FREE BACKUP WITH GRID EDGE SOLUTIONS

We now evaluate the back-up needs of the data center if supplied with a GES, which leverage automation and smart controls to operate the various assets in a coordinated and intelligent way. For example, GESs are necessary to enable advanced microgrid operation. With GES, solar PV can continue to generate power during supply disruptions from the main utility. GES also enable the BESS to provide multiple values to bridge the on-site renewable generation with back-up generators that run on imported fuels, including imported green hydrogen. The solar PV can reduce fuel requirements, while the BESS can help with its integration, particularly when large amounts of PV can be added. The fuel cell can be used in place of the diesel generator to increase renewable percentage, and the UPS is still included for bumpless transfer of critical loads directly after electric utility supply failures.

The various system back-up options presented here are modeled with the HOMER Pro energy simulation software [18]. The simulation is performed for the first 100 hours in the year, in January.

The analysis presented here provides detail on increasing renewable for back-up at the small 2MW data centers described previously, with qualitative discussion on designing for the larger 30 MW data centers.

The percent of load from renewable energy (RE) presented here is calculated by determining how much of the load is not served by the back-up diesel gensets.

A. Small data center (2MW load) with land constraints in southern Europe

First, we design a PV-BESS-diesel/UPS system for a data center with space and land constraints. This is a practical constraint for data centers in urban areas or other locations where land area is a challenge. If we limit the solar PV to that which fits on the 400 m^2 roof calculated previously, grid edge solutions allows this local renewable generation, on average, to offset only about 0.5% of the load over the 100 hour outage. When paired with a BESS to ensure high power quality and improved generator-set efficiency/operation, it results in a 0.4% fuel savings.

If we enhance the design further to replace the diesel genset with a fuel cell powered by imported green hydrogen, it would require just under 12 tons of hydrogen (H_2). The results are summarized in Table 4.

Table 4. Comparing GES for 100-hour back-up of small (2MW) data center in South Europe with no additional land available

Major back-up assets	PV, kW_p	BESS, MW/MWh	Percent load from RE	H_2, ton	Diesel fuel, liters
Diesel/ UPS	0	0 / 0	0%	0	65000
PV/BESS/ Diesel/ UPS	56	.25/.25	0.4%	0	64700
PV/BESS/ Fuel cell/ UPS	56	.25/.25	100%	12	0

B. Small data center (2MW load) without land constraints in Southern Europe

We now explore the land requirements for solar PV if a data center wants to back-up significant amounts of its load with solar. Access to land enables the data center to serve more load with local solar power. Where land area is unavailable, imported green hydrogen with a fuel cell can enable the system to have 100% back-up from renewable energy.

If a small 2MW data center in South Europe wants to draw 5% of its backup from local solar, it would take a 800 kW_p PV array with 1 MWh BESS. The solar would require about 5700 m^2 of area, divided between available rooftop space and nearby land. The remaining load can be served by diesel gensets that use 62,000 liters over the 100-hour outage; this represents a 5% fuel savings. Alternatively, for a data center backed-up with 100% renewable sources, the back-up diesel gensets could be replaced with fuel cells that require about 11 tonnes of green hydrogen. See summarized results in Table 5.

Table 5. Comparing GES for 100-hour back-up of small (2MW) data center in South Europe with land available be renewable level

Config	PV, kW_p	BESS, MWh	Percent load from RE	H_2, ton	Diesel fuel, liters	Solar area, m^2
Diesel/ UPS	0	0	0%	0	65000	0
PV/BESS / Diesel/ UPS	800	1	5%	0	62000	5700
PV/BESS / Diesel/ UPS	3500	15	25%	0	49000	25000
PV/BESS / Diesel/ UPS	8500	30	50%	0	32000	60700
PV/BESS / UPS	13000	89	100%	0	0	92900
PV/BESS / Fuel cell/ UPS	800	1	100% (5% from onsite PV)	11	0	5700

C. Small data center (2MW load) in the Nordic region

Considering a small 2MW data center in the Nordic region of Europe, we find that more land is required for the solar, increasing the need for imported energy for back-up, whether from diesel fuel or green hydrogen to pursue 100% renewable back-up.

Because the evaluation is performed at a time of year unfavorable to solar radiation, in early January, we find that the on-site solar PV unable to contribute significant amounts of energy. It is not feasible for on-site solar PV to contribute significantly in mid-winter except through storing energy in the BESS. To meet the back-up load requirements with significant amounts of renewable energy, imported green fuel is required. Therefore, a reduced set of results without solar PV are summarized in Table 6.

Table 6. Comparing GES for 100-hour back-up of small (2MW) data center in Nordic Europe by land and renewable level

Config	BESS MWh	Percent load from RE	H_2, ton	Diesel fuel, liters
Diesel/ UPS	0	0%	0	65000
BESS/ UPS (see text)	275	100%	0	0
Fuel cell/ UPS	0	100%	12	0

The BESS/UPS design includes no solar PV. This scenario is included in the table to show that a large BESS fully-charged with renewable energy would be necessary to serve the load without importing energy as fuel. It is important to note that if the outage occurred at a different time of year, such as the summer, onsite solar PV could support the load.

D. Large data center (30 MW load)

The considerations for the large data center back-up needs are like the small data center, although the scale is increased. At this level of indicative analysis, the factors presented can be multiplied by the ratio of the load. For example, the 100% renewable back-up based on PV/BESS/UPS for a 30 MW data center in Southern Europe would require 15 times as much land, or about 1.4 million m^2.

V. INDICATIVE TOTAL COST OF OWNERSHIP

The costs of these scenarios vary significantly. We calculate high-level total cost expectations for each of the six options presented for the small data center in Southern Europe. We assume a real discount rate of 3% and 20 year project lifetime. We make the following additional cost assumptions, summarized in Table 7.

Table 7. Summary of additional economic inputs

Technology	Installed capital cost	Annual Fixed operating expense	Variable (non-fuel) operating expense	Fuel cost
Diesel	€1150/kW	€34.5/kW	€0.02/kWh	€1.25/L
PV	€1650/kW	€17/kW	-	-
BESS	€400/kWh$_{cap}$	€9/kW	€0.0003/kWh	-
Fuel cell	€7000/kW	€34.5/kW	€0.0006/kWh	€6/kg

The costs are applied to the sizing results indicated in Table 5. In addition, we assume that the generation from solar PV will provide revenue of €0.05/kWh for each unit of energy generated during normal operation (i.e. not during back-up). BESS are also able to generate revenue during normal (non-back-up) operation by participating in ancillary service (A/S) markets. We assume the BESS will create €40/kWh$_{cap}$ of revenue for each unit of installed capacity. The resulting present values for the total cost of ownership (TCO) for back-up cost, revenue, and net TCO are summarized in Table 8.

Table 8. Summary of total cost of ownership (TCO) for small data center without land constraints in Southern Europe

Config	PV, kW$_p$	BESS, MWh	TCO for Back-up, Million €	BESS A/S and PV revenue, Million €	Net TCO, Million €
Diesel/ UPS	0	0	4.58	0	4.58
PV/BESS/ Diesel/ UPS	800	1	6.37	1.47	4.90
PV/BESS/ Diesel/ UPS	3500	15	16.54	12.76	3.78
PV/BESS/ Diesel/ UPS	8500	30	28.07	27.16	0.91
PV/BESS/ UPS	13000	89	61.98	67.20	-5.22
PV/BESS/ Fuel cell/ UPS	800	1	17.16	1.47	15.68

The total costs presented are indicative values that capture the total cost in net present euros, including capital costs, operating costs, and fuel costs. The architecture option with very large PV and BESS incurs the greatest costs, but also has the greatest potential from revenue from selling energy generation from the solar PV and ancillary services from the BESS.

Just as the back-up architecture requirements depend significantly on the energy requirements of the data center, the revenue that solar PV and BESS receive will depend significantly on the market conditions. However, the results here show that there is significant potential value from using back-up infrastructure investments to produce revenue during normal day-to-day operations.

VI. CONCLUSION

We find that the system design is affected by the climate, the facility size, facility energy density, available land, and the final percentage of back-up that is derived from renewable and other carbon-free generation.

Land constraints should be considered for the described pathways; even with one cycle over the year, the land requirements for solar PV can range from 4-6 times expected data center roof top (when coupled only with BESS), to 10 times (when coupled with hydrogen). Data center tier design, the geographical latitude and the density of equipment/energy for the data center can affect grid edge solution selected. As of now however, even considering a monthly 2% self-discharge in batteries, the overall annual battery efficiency remains higher comparing to the efficiency of H_2 fuel cells.

Using more cycles per year for the BESS or hydrogen electrolyzer/fuel cell pair, results in better utilization of these assts during a potential utility grid downtime. This can help with the investment cost. However, the further increase in land footprint could be an important limitation.

Although there are physical siting challenges with having adequate on-site renewables to power data centers with 100% on-site renewables for back-up, there are opportunities today to reduce the use of fossil fuels. Generating all of the required energy with local solar PV requires significant land area and is likely infeasible for many data centers. However, by combining with a dispatchable generator that runs on fuel from renewable sources, such as a fuel cell run on green hydrogen, it is possible to simplify the logistics. The options can be customized to the site to maximize the use of solar on the available land while minimizing the hydrogen that must be imported to the site.

We also demonstrate the value of selling services from back-up infrastructure investments into energy and ancillary service markets. Solar PV and BESS can, respectively, sell these services to generate revenue that can offset investment costs. If market conditions are favorable, and there is adequate space for siting, BESS and solar PV technologies can be a net revenue source, rather than a cost.

The work presented here also demonstrates that a study is important for selecting the preferred combination of technologies for data center back-up. This paper focused exclusively on considerations for back-up. However, a grid edge solution will also provide benefits during normal utility operation. These can include selling solar energy into the energy market, providing a variety of services with the BESS into ancillary services markets, as well as network stabilization [19]. A comprehensive techno-economic study factoring in area constraints, geography, market access, network needs, data center energy requirements, and renewable goals are important for determining the preferred grid edge solution mix for backing-up a data center with increasing amounts of renewable energy.

BESS technology has already matured significantly and will likely be an increasing part of back-up for data centers; fuel cells provide an option that will continue to expand with the growth of the "hydrogen economy". Technological innovation, and improved cost efficiencies will open up new power supply options for 100% renewable back-up with a range of options.

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