The Reality of Replacing Diesel Generators with Natural Gas, Energy Storage, Fuel Cells & Other Options

White Paper 14

Version 2

by Allegia Wiryawan and Carsten Baumann

Executive summary

Diesel generators have long been the power backup for critical applications. However, with emerging environmental concerns, data center operators are looking to replace them with more sustainable options. In this paper, we assess many alternative technologies and narrow down our comprehensive evaluation to three technologies: natural gas generators, lithium-ion battery energy storage systems, and proton exchange membrane (PEM) fuel cells. These technologies are evaluated on their environmental impacts, cost, and other relevant criteria. Our analysis concludes that there is no obvious choice for a direct replacement of diesel generators for a long runtime backup-only application. The most practical alternatives today are using either natural gas generators or sustainable diesel fuel options. Lithium-ion batteries are not well-suited for 24-hour backup. While PEM fuel cells are the main contender from an emissions' standpoint, this technology requires further cost reduction in CAPEX and fuel cost to become economically feasible.

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Introduction

Diesel generators have long been a staple in data centers and other mission critical applications, serving the role of an emergency/standby power source. However, reliability and resiliency are no longer the only concerns of data center owners and operators. According to a survey of multi-tenant data centers by 451 Research, customers are increasingly requiring data center operators to have sustainability commitments. This topic is discussed in detail in White Paper 64, *Why Data Centers Must Prioritize Environmental Sustainability: Four Key Drivers*. Furthermore, in July 2020, Microsoft announced their goal to eliminate their dependency on diesel fuel for backup power in their data centers by 2030. Considering the typical lifetime of backup generators is 20+ years, there is an urgency to find a suitable sustainable replacement now. Also, some locations, such as California, have stricter emissions requirements that discourage the deployment of diesel generators there. Hence, there is growing interest in sustainable alternatives to diesel generators. This paper will explore these alternatives, and thus can help data center operators in evaluating these options. To do so, we first evaluate diesel generators as a baseline to compare against alternatives. Alternative technologies are then assessed and narrowed down to the most likely alternatives for long-duration standby power (hours to days, and not seconds or minutes). These technologies are further evaluated across the same criteria as diesel generators. Finally, the results are summarized, and we determine if there's a sustainable replacement for diesel generators.

Be aware that there are many potential options for genset replacement, and a comprehensive view is beyond the scope of this paper. Particularly, this paper does not evaluate the following options: onsite prime power generation, emerging technologies, and geographic-dependent technologies, though commentary on many of those technologies is provided.

Evaluating diesel generators

In terms of technology maturity, diesel generators are very mature with a global installed base estimated at around 36 to 47 GW (not specific to data centers). From 2020 to 2027, they're forecasted to have a 5-8% compound annual growth rate (CAGR).[1,2] As a baseline for comparing other backup technologies, we evaluated diesel generators against the following criteria: environmental impacts, cost, and other characteristics.

Environmental impacts

There are two key environmental impact metrics we must evaluate: air quality and greenhouse gas (GHG) emissions. Each of these have various health and environmental impacts, thus many local jurisdictions impose a limit on diesel generators' operating hours (for example California). For this reason, diesel generators typically only operate when providing backup power for data centers or when undergoing maintenance tests.

Air quality

The air quality metric refers to emissions other than GHGs from operating the technology. Diesel generators emit several non-GHG pollutants when in operation: nitrous oxides (NO_x)[3], particulate matter (PM), volatile organic compounds (VOC), sulfur dioxide (SO_2), and carbon monoxide (CO). We will focus only on the following air quality pollutants: NO_x and PM, as these are the ones that differ between an Environmental Protection Agency's (EPA) Tier 2 and Tier 4 certified diesel generators[4].

[1] Grand View Research, *Diesel Generator Industry Market Report 2020*

[2] Global Market Insights, *Diesel Generator Market Report 2020*

[3] NO_x can react to form nitrous oxide (N_2O), which is a GHG and included in Scope 1 calculations

For this paper, the NO_x and PM emissions are the EPA's emissions standards for diesel generator sets above 560 kW in capacity, as listed in **Table 1**. Tier 4 diesel generators offer significant reduction in emissions compared to Tier 2 diesel generators. The selection between Tier 2 and Tier 4 certified diesel generators may depend on local regulations and desired applications. Currently, generators used only for emergencies must be at least Tier 2 certified. But they are much more limited in operating hours due to their higher emissions. Tier 4 certified diesel generators are required for non-emergency applications.

Table 1

Emission rates from diesel generators' operation

Emission rate	EPA Tier 2[4] diesel generator	EPA Tier 4[4] diesel generator
Air quality		
NO_x (kg/MWh)	6.4	0.67
PM (kg/MWh)	0.2	0.03
GHG emissions[5]		
CO_2 (kg/gallon)	10.20	
CH_4 ($kgCO_2e$/gallon)	0.01	
N_2O ($kgCO_2e$/gallon)	0.02	

Greenhouse gas (GHG) emissions

Diesel generators emit several GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous dioxide (N_2O). Furthermore, there are 3 categories of GHG emissions: Scope 1, Scope 2, and Scope 3.

- Scope 1 GHG emissions refer to direct CO_2 equivalent emissions produced onsite from operating the technology.
- Scope 2 GHG emissions refer to indirect CO_2 equivalent emissions from purchased electricity, steam, heat, or cooling.
- Scope 3 GHG emissions refer to all other indirect CO_2 equivalent emissions in both upstream and downstream activities. For this paper, Scope 3 GHG emissions are limited to those from the production of the fuel (pre-combustion emissions) and manufacturing the technology (embedded carbon)[6].

Scope 1 – As can be seen in **Table 1**, Scope 1 GHG emissions for diesel generators are dominated by CO_2 emissions while they are producing power. Unlike NO_x and PM, there are no differences in GHG emissions between a Tier 2 and Tier 4 diesel generators. Based on a few technical specifications, they consume around 265 liters (70 gallons) of diesel per megawatt hour (MWh). This translates to around 714 kg of CO_2 equivalent per MWh of generation ($kgCO_2e$/MWh). However, there are more sustainable alternatives to diesel fuel such as biodiesel and renewable diesel which is explored in **Appendix 2**.

Scope 2 – Diesel generators have no Scope 2 GHG emissions.

Scope 3 (fuel production) – While most diesel generators' GHG emissions are produced during their operations, the diesel fuel supply chain also produces

[4] Diesel Net - EPA standards for non-road diesel generator; Table 1 & Table 4: gensets above 560 kW

[5] EPA's Emission Factors for GHG Inventories (April '21) - Table 1: mix of distillate fuel #1 and #2. Emission factors of CHUU4 and N_2O originally listed in g/gallon, converted to $kgCO_2e$/gallon with GWP factors listed on the top of the document. For CHUU4: 0.415 g/gallon = 0.000415 kg/gallon x 25. For N_2O: 0.08 g/gallon = 0.00008 kg/gallon x 298.

[6] Scope 3 GHG emissions in this paper does not include transportation of the equipment

greenhouse gas emissions. This is part of the diesel generator's Scope 3 emissions. The amount of GHG emissions depends on where the diesel fuel is produced and consumed, especially the refineries. For this paper, we're assuming the end user is in California, USA as we're using values published by the California Air Resources Board (CARB)[7]. Accounting for the efficiency of diesel generator, producing and transporting diesel fuel emits 259 $kgCO_2e/MWh$[8].

Scope 3 (embedded carbon) – Assumptions about the origin of materials, location of manufacturing, and where it's installed can greatly change the calculations for generators' embedded carbon. Hence, the numbers presented here (and for the other technologies) are only to be used as a general indicator and for comparison, not suitable for carbon accounting. For materials extraction and processing emissions, assume diesel generators are mostly made of steel and iron.[9] For emissions from the assembly of diesel generators, we used values from Caterpillar's 2020 Sustainability Report[10]. Combining these two emissions, we estimate that the embedded carbon is around 22,000 $kgCO_2e/MW$. Tier 4 diesel generators will only have a small incremental increase in embedded carbon due to the additional filter system needed.

Cost

As befitting of the incumbent technology, diesel generators perform extremely well on cost metrics, specifically, capital expenditure (CAPEX) and operating expenditure (OPEX). CAPEX includes installation and integration costs, and OPEX includes maintenance and fuel costs.

CAPEX

All-in, EPA-certified Tier 2 diesel generators cost around $600 to $800 USD per kW of capacity. This is at nameplate capacity (i.e., no oversizing factor is applied) and includes the generator, installation, engineering, commissioning, and procurement costs. The lower emissions, EPA-certified Tier 4 diesel generators cost around $800 to $1,200 USD per kW. As we will later show, even the Tier 4 diesel generators remain a very cost competitive solution for backup power applications.

As diesel generators are a mature technology, they are already cost-optimized and there's little room for any further price reductions. However, based on the cost trend of raw materials, we predict that the acquisition cost will sightly increase.

OPEX

As shown in the EIA graph in **Figure 1**, the average diesel fuel cost in the USA has historically ranged from slightly below $1.00/gal in 1999 to more than $5.00/gal in 2022. In the first quarter of 2022, it has ranged from $3.72/gal to $5.10/gal. For comparison, in Ireland diesel prices have ranged $6.58/US gal to $8.08/US gal[11] in the first quarter of 2022, significantly higher than the USA. In China, diesel prices ranged from $4.05/gal to $4.83/gal in the first quarter of 2022. In USA, generators can use diesel that are not subject to federal and state excise taxes – thus for

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[7] Assumes USA's average crude oil import and domestic production mix, refined into diesel in California's refineries, and a mix of pipeline and trucking transport to end user.

[8] *CARB's Pathway Technical Support Documentation*, Table B.1, p.11 - Initial value: 25.6 g of CO_2 eq. per MJ. Conversion factors used: 1,055MJ = 1 million metric BTU (MMBTU), 0.137 MMBTU per gallon of diesel, 70 gallons of diesel per MWh.

[9] International Energy Agency's value for steel production of 1.4 tons of CO_2 equivalent per ton of steel multiplied by diesel generator's weight estimate of 7 tons per MW.

[10] 35 tons of CO_2 equivalent per million dollars of revenue multiplied by cost estimate of a Tier 2 diesel generator, $350,000 per MW

[11] Original values: 1.58 €/liter to 1.94 €/liter. Conversion factors: 1 liter=0.246 US gallons, 1 €=1.10 USD

generators diesel price ranged from $3.16/US gal to $4.54/US gal in Q1 '22[12]. As mentioned earlier, a diesel genset consumes around 70 US gallons per MWh, hence this translates to a fuel cost range from $221/MWh to $317/MWh in the USA in 2021.

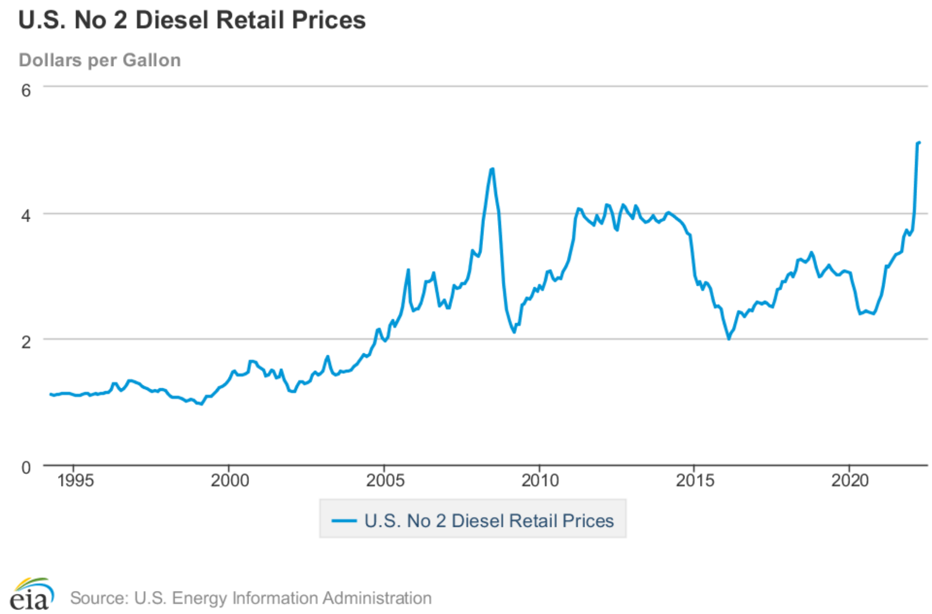

Figure 1

USA's Average Diesel Fuel Retail Price from EIA

Diesel generators require regular maintenance to prevent various issues, including running them at full load with a load bank to prevent wet stacking. Although different operators have different maintenance schedules and procedures, we assume a monthly maintenance schedule, including an engine exercise schedule of one hour[13]. The annual maintenance cost, without fuel expense, for diesel generators increases with the size of the generator plant. In this analysis, we assume an industry average annual cost range of $9,000/MW - $10,000/MW.

Other characteristics

Along with the above metrics, there are three other characteristics when evaluating different technologies against diesel generators: physical space, fuel availability, and start-up duration.

Physical space – Diesel generators offer a favorable footprint, especially when including on-site fuel storage. This is because diesel is one of the densest fuels in terms of volume. Even though diesel generators have only an efficiency of around 30%, 24 hours' worth of diesel fuel can be stored in a belly tank underneath the diesel generator. Hence, on-site fuel storage does not take up space in addition to the diesel generator. A 1 MW diesel generator with 24 hours' worth of fuel storage in its belly tank has a footprint of approximately 11 square meters (120 sq. ft.), not including any required clearances.

Fuel availability – According to the Energy Information Administration (EIA), nearly 29 million barrels of diesel fuel were consumed per day globally in 2018. This translates to an estimated annual consumption of 60 quadrillion BTU[14]. It implies that there's a very robust supply chain of diesel fuel that data center operators can tap into to ensure diesel fuel is available wherever and whenever. Although many data

[12] From *EIA's FAQ*, Average federal and state taxes on diesel is $0.57/US gal

[13] We assume engine exercise is performed at nameplate capacity for the full hour

[14] EIA: 1 barrel of diesel = 5.772 million BTU per barrel in 2018

center operators have multiple service-level agreements to ensure delivery during emergencies, it can be challenging to procure diesel fuel deliveries in the aftermath of a natural disaster.

Start-up duration – For reliability and in some cases, regulatory purposes, the backup power solution must be able to turn on and serve 100% of load capacity in a short period of time. Diesel generators can do so within 10 seconds.

Summary of diesel generator evaluation criteria

Table 2 summarizes the diesel generator evaluation characteristics. We use these same characteristics when evaluating alternative technologies. The annual values are calculated with the following assumptions: 1 MW rated capacity with 1 MW of load, 1 hour of maintenance per month and 4.7 hours of power outage per year (the average in the US in 2019).

Table 2

Diesel generator characteristics

Characteristic	Diesel generator	
Maturity of technology (global installed base; global CAGR 2020-2027)	36-47 GW; +5-8%	
Annual environmental impacts (16.7 operating hours)	EPA Tier 2	EPA Tier 4
NO_x emissions (kg/MW)	106.9	11.2
PM emissions (kg/MW)	3.34	0.50
Scope 1 GHG emissions (kgCO_2e/MW)	11,924	
Fuel production GHG emissions (kgCO_2e/MW)	4,325	
Embedded carbon (kgCO_2e/MW)	22,000	
Cost (16.7 operating hours)	EPA Tier 2	EPA Tier 4
CAPEX ($/MW)	$600K - $800K	$800K - $1,200K
Annual fuel cost ($/MW)	$3,691 - $5,294	
Annual maintenance cost ($/MW)	$9,000 - $10,000	
Other considerations	EPA Tier 2	EPA Tier 4
Footprint w/out clearance requirements (m^2/MW)	11	
Global fuel availability	60 quadrillion BTU (2018)	
Start-up duration (seconds)	<10	

Evaluation of alternatives

There are a wide variety of alternative technologies and fuels to diesel generators for long runtime backup applications. We narrowed them down to three for deeper evaluation: natural gas generators, lithium-ion battery energy storage systems (BESS), and proton exchange membrane (PEM) fuel cells. Three criteria were used to select these alternatives, the technology is: suitable for backup power, not dependent on geographic features (e.g., pumped hydro), and a reasonably mature technology. To consider fuel sources for further evaluation required an equal or better energy density to diesel, a lower GHG emissions profile, and the general availability of the fuel itself. Appendix 1 describes the detailed analysis that led to the three selected alternatives.

Assumptions

To ensure an objective comparison, we use the same assumptions as we did for evaluating diesel generators. We list these assumptions again in Table 3. While some technologies do not require monthly full load tests, we conservatively applied a one hour per month maintenance test (except for the lithium-ion BESS), and the previously referenced annual outage duration of 4.7h. For the PEM fuel cells and lithium-ion BESS technologies that natively produce direct current (DC) power, the CAPEX included inverter costs – as we assume that most of today's facilities, like data centers, use alternating current (AC) distribution. We do not include energy consumption of the auxiliary systems of the evaluated technologies in our calculations. The same was done previously for diesel generators.

Table 3

Assumptions used for evaluation

Assumptions	
Load at 100% rated capacity	1 MW
Oversizing factor	1x (Nameplate capacity)
Backup-time	24 hours
Maintenance run-time	1 hour/month
Outage duration	4.7 hours/year
System scope	Up to AC output
System connection	At main switchboard
Installation connection	Outdoors

Natural gas generators

Of all the technologies evaluated, only natural gas generators allow for a direct 1:1 replacement. They have similar footprints and electrical interfaces. They differ about on-site fuel storage, as explored in subsequent sections. As illustrated in later sections, using natural gas as fuel allows for significant emissions reduction without significant increase in CAPEX, and potentially offers improvements in OPEX. Natural gas generators are built to be operated in two ways: lean burn or rich burn. Lean-burn natural gas generators operate with a higher air to fuel ratio than rich-burn natural gas generators. This leads to a difference in emissions (detailed below), and load response capabilities. Rich-burn natural gas generators can run under a wider range of ambient conditions without requiring derating and have similar performance to diesel generators[15]. Lean-burn natural gas generators have higher electrical efficiency, but generally perform poorly with varying loads – though some manufacturers have addressed this with advanced electric control of the generator's engine[16]. For a more detailed comparison between natural gas generators and diesel generators, please refer to White Paper 286, *Applying Natural Gas Engine Generators to Hyperscale Data Centers*. Table 4 summarizes characteristics of natural gas generators.

Environmental impacts

Air quality – One of the clear advantages natural gas generators have over diesel generators are significant reductions in emissions. Lean burn natural gas generators have the same NO_x emission rate as EPA-certified Tier 4 diesel generators and a PM emission rate 10% lower than Tier 4 diesel generators. Meanwhile, rich burn natural gas generators have a 96% lower NO_x emission rate[17], and 90% lower PM emission rate over EPA-certified Tier 4 diesel generators.

[15] Generac, *Benefits of a Rich Burn Engine Generator in a Standby Application*

[16] Caterpillar, *Natural Gas Generator Sets for the Standby Market*

[17] Rich burn natural gas generators tend to be equipped with a three-way catalyst that significantly reduces NO_x emissions (Generac, *Benefits of a Rich Burn Engine Generator in a Standby Application*)

Scope 1 GHG emissions – Lean burn natural gas generators are more efficient than rich burn natural gas generators, as the latter consumes more fuel[18]. Based on the natural gas' emission rates from EPA's Emission Factors for GHG Inventories table: lean burn natural gas generators emit around 425 $kgCO_2e/MWh$, 40% less than diesel generators in Scope 1 GHG emissions. While rich burn natural gas generators emit around 637 $kgCO_2e/MWh$, 11% less than diesel generators. Although lean burn natural gas generators consume significantly less fuel than rich burn natural gas generators (resulting in less GHG emissions), they produce more PM and NO_x emissions.

Scope 2 GHG emissions – Natural gas generators have no Scope 2 GHG emissions.

Table 4

Natural gas generator characteristics

Characteristic	EPA Tier 4 diesel generator	Natural gas generator	
Maturity of technology (global installed base; global CAGR 2020-2027)	36-47 GW; +5-8%	7.7-9.2 GW; +10.7%	
Annual environmental impacts (16.7 operating hours)		Lean burn	Rich burn
NO_x emissions (kg/MW)	11.2	11.2	0.53
PM emissions (kg/MW)	0.50	0.45	0.05
Scope 1 GHG emissions ($kgCO_2e/MW$)	11,924	7,098	10,638
Fuel production GHG emissions ($kgCO_2e/MW$)	4,325	2,605	3,907
Embedded carbon ($kgCO_2e/MW$)	22,000	26,400	
Cost		Lean burn	Rich burn
CAPEX ($/MW)	$800K - $1,200K	$1,000K - $1,300K	
Annual fuel cost ($/MW)	$3,140 - $3,841	$1253 - $1,286	$1,887 - $1,937
Annual maintenance cost ($/MW)	$9,000 - $10,000	$9,000 - $10,000	
Other considerations		Lean burn	Rich burn
Footprint w/out clearance requirements (m^2/MW)	11	30-32	
Global fuel availability	60 quadrillion BTU	148 quadrillion BTU	
Start-up duration (seconds)	<10	10-45	

Scope 3 (fuel production) – For the GHG emissions during fuel production, we continue to use CARB's values for our comparison[19]. This calculates to around 156 $kgCO_2e/MWh$ for lean burn natural gas generators (~40% less than diesel generators) and 234 $kgCO_2e/MWh$ for rich burn natural gas generators (~10% less than diesel generators). As with diesel, the production emission factor for natural gas may differ greatly when considering other natural gas production sources, and end-use location. CARB assumes the majority of California's natural gas is imported from Canada and Texas and transported via pipeline.

[18] Lean burn natural gas generators' average consumption rate: 8,440 MJ/MWh (8 MMBTU/MWh). Rich burn natural gas generators': 12,660 MJ/MWh (12 MMBTU/MWh). Based on several technical specifications. Conversion factor: 1MMBTU = 1055 MJ

[19] *CARB's Pathways Technical Support Documentation* , Table C1, p.18 - Natural gas' production and transport to California emits 18.5 g of CO_2 equivalent per MJ, lean burn NG: 8,440 MJ/MWh, rich burn NG: 12,660 MJ/MWh

Environmental sustainability of natural gas generators can be further improved by only using renewable natural gas (RNG). Though essentially the same as conventional natural gas, RNG is produced through biogas that is captured from landfills, livestock operations, and other organic waste sources[20]. Depending on how RNG is produced, such as ones from livestock operations, they can be carbon negative as they capture and use existing methane sources[21]. RNG is also referred to as biomethane. CARB's Temporary Pathway for Fuels calculates that liquefied biomethane from landfill has a carbon intensity 10% lower than conventional liquefied natural gas. Meanwhile, CARB calculates that if the liquefied biomethane is produced from manure, its carbon intensity is 258% lower than conventional liquefied natural gas. However, RNG is not widely available.

Another point of consideration is manufacturers are already offering and continuing to develop natural gas generators that can be fueled with a blend of natural gas and hydrogen, with the end goal of making purely hydrogen-fueled generators. A 100% hydrogen generator will not emit CO_2 and PM. It will also produce only a small amount of NO_x emissions. However, the power output will be lower when including hydrogen in the fuel mix.

Scope 3 (embedded carbon) – While there are differences in the engine designs used for natural gas generators and diesel generators, they tend to be made of the same materials and have similar manufacturing processes. Comparing various technical specifications of these generators, natural gas generators weigh around 20% more than diesel generators to achieve the same output capacity. Thus, for natural gas generators we assumed embedded carbon is 20% more than diesel generators.

Cost

CAPEX – The value listed in **Table 4** includes the generator, installation, engineering, commissioning, and procurement costs. This is a slight premium over an EPA-certified Tier 2 diesel generators, but comparable to Tier 4 diesel generators. There's no significant difference in cost between lean burn and rich burn natural gas generators. Like diesel generators, natural gas generators are a mature technology, and therefore already cost-optimized.

OPEX – Per the EIA, natural gas has historically ranged from around \$5 to \$14 per MMBTU[22]. In the first two months of 2022, it has ranged from \$9.41 to \$9.67 per MMBTU[21]. For comparison, in the same time period, Japan's liquified natural gas (LNG) import price ranged from \$14.69 to \$17.00 per MMBTU and European Union's ranged from \$27.23 to \$28.26 per MMBTU. In the USA, fuel cost for lean burn natural gas generators ranged from \$75 to \$77 per MWh – 66% to 76% lower than for diesel generators. While, for rich burn natural gas generators, fuel cost range of \$113 to \$116 per MWh – 49% to 63% lower than for diesel generators. From a maintenance perspective, however, natural gas generators and diesel generators have similar annual maintenance cost.

Other characteristics

Physical space – Natural gas generators with on-site storage (propane tanks) are 173% to 191% bigger than diesel generators. Based on the generator packaging, natural gas generators can be approximately 20% bigger engine for the same nameplate capacity. There is also an increase in size of on-site storage tanks as both propane and LNG have lower fuel densities than diesel.

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[20] USA's Department of Energy's Alternative Fuels Data Center – Renewable Natural Gas

[21] Trillium Energy, *How Can Renewable Natural Gas Provide a Negative Carbon Impact?*

[22] 1,000 cubic feet of natural gas = 1.037 MMBTU in 2020 in the USA, per the EIA

Fuel availability – Although, it is possible to have on-site storage through propane or LNG tanks, natural gas is typically not stored on-site, and instead requires a pipeline connection. The natural gas pipeline infrastructure also acts as a quasi-storage system, and it has been argued that they have higher reliability compared to the electrical distribution networks[23], and are semi-independent of each other. Furthermore, per the EIA's database, natural gas had an annual global production of 148 quadrillion BTU in 2019. This signifies that it has a robust supply chain, potentially even more so than diesel in some regions.

Start-up duration – Natural gas generators tend to have longer start-up duration than diesel generators. On average, it requires 45 seconds to go from off to 100% capacity. However, some manufacturers offer natural gas generator models with similar start-up duration as diesel generators of 10 seconds.

Lithium-ion battery energy storage system (BESS)

Lithium-ion BESS is currently the dominant energy storage technology. It has reached scale through the consumer electronics and automotive industries and has started to be deployed as a resource for electric grids and electric utility customers. According to *Bloomberg New Energy Finance's 2021 Global Energy Storage Outlook*, 17 GW/34GWh of stationary energy storage has been deployed globally by the end of 2020 – around double the amount of natural gas generators deployed globally today. However, most of these BESS only have a runtime of around two to four hours which is used for grid resiliency and improved integration with renewables. According to Wood Mackenzie, energy storage is predicted to have significantly higher deployments with a CAGR of +31% from 2020 to 2030. **Table 5** summarizes characteristics of lithium-ion BESS, with explanations and rates detailed in the following sections.

Table 5

*24-hour Lithium-ion BESS characteristics, *lithium-ion BESS' annual values assume 4.7 operating hours/year*

Characteristic	EPA Tier 4 diesel generator	Lithium-ion battery energy storage system*
Maturity of technology (global installed base; global CAGR)	36 – 47 GW; +5-8%, 2027	17 GW (stationary); +31%, 2030
Annual environmental impacts (16.7 operating hours)		
NO_x emissions (kg/MW)	11.2	0
PM emissions (kg/MW)	0.50	0
Scope 1 GHG emissions (kgCO_2e/MW)	11,924	0
Fuel production GHG emissions (kgCO_2e/MW)	4,325	1,844
Embedded carbon (kgCO_2e/MW)	22,000	1,224,000
Cost		
CAPEX ($/MW)	$800K - $1,200K	$7,000K - $9,500K
Annual fuel cost ($/MW)	$3,140 - $3,841	$545 - $658
Annual maintenance cost ($/MW)	$9,000 - $10,000	$30,000 - $45,000
Other considerations		
Footprint w/out clearance requirements (m^2/MW)	11	111-139
Global fuel availability	60 quadrillion BTU	Depends on electric grid
Start-up duration (seconds)	<10	<0.1

[23] NREL, *A Comparison of Fuel Choice for Backup Generators*, Pages 10-12

Unlike other technologies, lithium-ion BESS do not require monthly load testing. In addition, instead of being fueled and operated like the other technologies, batteries are also discharged for uses other than outages and charged locally to restore storage reserves.

Environmental impacts

Air quality – Lithium-ion BESS have no PM or NO_x emissions when operating. This removes the requirement of air quality permits for installation, which some customers have expressed difficulty in obtaining for their diesel generators.

Scope 1 GHG emissions – Unlike diesel and natural gas generators, lithium-ion BESS have no GHG emissions when operating.

Scope 2 GHG emissions (fuel production) – As the lithium-ion BESS are powered by electricity, their fuel production GHG emissions are counted as Scope 2. To be consistent with the other technologies' fuel production's GHG emissions, we use California's grid's average carbon intensity[24] when assessing the GHG impact of battery charging. This calculates to around 392 $kgCO_2e/MWh$[25], 51% higher than diesel generators' fuel production GHG emissions on a per MWh basis. However, depending on how BESS are used, it can reduce a site's Scope 2 GHG emissions. A BESS that's charged with excess power from renewables and dispatched when the grid is primarily relying on fossil fuels, results in a reduction of BESS' – and thus the site's – Scope 2 GHG emissions. As no monthly load testing is required, BESS' fuel production GHG emissions on an annual basis is 57% lower than diesel generators with no special charging schedule.

Scope 3 (embedded carbon) – Lithium-ion BESS have a significantly higher embedded carbon profile compared to generators. This is because its components (lithium and other minerals) require a more energy intensive extraction process compared to generators (steel, aluminum, etc.). Also, lithium-ion BESS have a lower energy density compared to diesel, thus requiring more materials for the same energy amount. We assume that BESS deployed consist of lithium iron phosphate (LFP) batteries produced in China[26]. Thus, 24-hour lithium-ion BESS' embedded carbon is around 5,464% greater than diesel generators. White Paper 71, *Understanding the Total Sustainability Impact of Li-ion UPS batteries*, provides more information on other environmental impacts of lithium-ion batteries.

Cost

CAPEX – While lithium-ion batteries have experienced a 97% reduction in cost since 1991[27], they remain cost-optimal only for 2 to 6 hours of run-time. Furthermore, unlike the other technologies evaluated in this paper, lithium-ion batteries do not allow independent scaling of power and energy. To scale a lithium-ion BESS to 24-hours of runtime requires linearly increasing the lithium-ion battery packs. The CAPEX listed in **Table 5** includes the battery packs, inverter, containerization, engineering, procurement, and commissioning cost. At 24 hours of runtime, lithium-ion BESS' CAPEX is around 692% to 775% more than the diesel generator CAPEX. However, unlike diesel and natural gas generators, lithium-ion batteries costs are expected to decrease continually over the next decade.

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[24] *CARB's Pathways Technical Support Document*, Table E.1, p.27: 93.75 gCO_2e/MJ, note: 1 MWh = 3,600MJ

[25] Pacific Northwest National Laboratory: lithium-ion's roundtrip efficiency is 86%

[26] Georg Bieker, *A global Comparison of the Life-cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars*, ICCT, 2021, Table 2.3

[27] David L. Chandler, MIT News, *Study reveals plunge in lithium-ion battery costs*, March 23, 2021

OPEX – The energy cost to charge a lithium-ion BESS depends on the cost of electricity and the roundtrip efficiency (charging and discharging cycle). In the USA, on average a commercial customer pays from $0.10 – $0.12 per kWh. For comparison, in China, it's also around $0.10/kWh[28], and in Ireland it has ranged from $0.12 to $0.14/kWh[29]. Hence, in the USA charging cost ranges from $116 to $140 per MWh[25], 48% to 56% less than diesel fuel on a per MWh basis. As BESS do not require monthly load testing, their annual fuel cost is 85% to 88% less than diesel generators. The maintenance cost of a BESS is primarily driven by the number of battery racks, as a service requires physical inspection of each module in a rack. 24-hour lithium-ion BESS' annual maintenance cost is 233% to 350% greater than diesel generators. Hence, the annual OPEX is primarily driven by the maintenance cost.

Other characteristics

Footprint – Lithium-ion battery packs have lower energy density compared to diesel fuel. Thus, their footprint is 909% to 1,164% greater than diesel generators.

Fuel availability – As electricity is the "fuel" for a BESS, the fuel availability is equivalent to the connected grid's availability, unless other onsite generation assets are available. A popular consideration is the use of photovoltaic arrays to charge the BESS with emission-free electricity.

Start-up duration – BESS has a very short start-up duration; dispatchable within 100ms, though this could be shorter depending on configuration and operating mode of the BESS as well as level of site control.

Proton exchange membrane (PEM) fuel cell

There are many types of fuel cells, and PEM fuel cells are most widely deployed. They scaled through automotive and material handling applications. Including these applications, 3.9 GW of PEM fuel cells have been deployed globally from 2010 to 2020[30], with a predicted CAGR of 31% from 2020 to 2027[31]. Table 6 summarizes characteristics of PEM fuel cell systems, with explanations and rates detailed in the following sections.

Environmental impacts

Air quality – PEM fuel cells emit only water vapor during operation; it has no NO_x or PM emissions. This removes the requirement of air quality permits for installation, which, again, some customers have expressed difficulty in obtaining for their diesel generators.

Scope 1 GHG emissions – Unlike diesel and natural gas generators, PEM fuel cells have no GHG emissions when operating.

Scope 3 (fuel production) – Depending on how hydrogen is produced, its fuel can be relatively carbon-free. Currently, hydrogen is predominantly produced from natural gas through steam methane reforming (SMR) and is referred to as "grey hydrogen", which emits around 946 $kgCO_2e/MWh$[32]. As a result, PEM fuel cells with grey

[28] Global Petrol Prices – Electricity Prices, September 2021

[29] Eurostat – Annual Electricity Price, 2010 to 2020 for non-household, medium-size consumers. Assumes 1€ = $1.10

[30] E4Tech's Fuel Cell Industry Reviews

[31] Market Research Future, *Hydrogen Fuel Cells Market to grow at a CAGR of 31.4% through 2027*

[32] *CARB's Pathways Technical Support Documentation*, Table F.3, p.37, for gaseous grey hydrogen (HYF): 117.67 gCO_2e/MJ of hydrogen produced, 120MJ of hydrogen = 1 kg of hydrogen. Assuming PEM fuel cell efficiency of 48%, PEM fuel cell consumes 67 kg to produce 1 MWh of electricity

hydrogen emit nearly the same amount of GHG emissions as diesel generators' Scope 1 and fuel production GHG emissions combined.

If hydrogen is produced from water through electrolysis powered by renewables, it's referred to as "green hydrogen." This process only produces 85 $kgCO_2e/MWh$[33], 91% lower than diesel generators' combined Scope 1 and fuel production GHG emissions. However, as discussed later, green hydrogen is currently significantly more expensive to produce compared to grey hydrogen. White Paper 513, *Making Sense of Hydrogen's Role in Reducing Greenhouse Gas Emissions*, provides more information on hydrogen.

Scope 3 (embedded carbon) – Like lithium-ion batteries, PEM fuel cell systems require minerals and materials that have carbon intensive extraction processes. Hence, they have a relatively high embedded carbon of around 112 $kgCO_2e/kW$[34]. Yet, this is a reduction of 91% of BESS' embedded carbon at this runtime, though still around a 409% increase compared to diesel generators.

Table 6

Proton exchange membrane fuel cell system characteristics

Characteristic	EPA Tier 4 diesel generator	PEM fuel cell system	
Maturity of technology (global installed base; global CAGR 2020-2027)	36-47 GW; +5-8%	3.9 GW; +31%	
Annual environmental impacts (16.7 operating hours)		Grey hydrogen	Green hydrogen
NO_x emissions (kg/MW)	11.2	0	
PM emissions (kg/MW)	0.50	0	
Scope 1 GHG emissions ($kgCO_2e/MW$)	11,924	0	
Fuel production GHG emissions ($kgCO_2e/MW$)	4,325	15,799	1,411
Embedded carbon ($kgCO_2e/MW$)	22,000	112,000	
Cost		Grey hydrogen	Green hydrogen
CAPEX ($/MW)	$800K - $1,200K	$2,100K - $2,500K	
Annual fuel cost ($/MW)	$3,140 - $3,841	$4,092 - $6,329	$6,329- $11,356
Annual maintenance cost ($/MW)	$9,000 - $10,000	$8,000	
Other considerations		Grey hydrogen	Green hydrogen
Footprint w/out clearance requirements (m^2/MW)	11	93-121	
Global fuel availability	60 quadrillion BTU	13 quadrillion BTU	N/A
Start-up duration (seconds)	<10	10-60	

Cost

CAPEX – Based on current prices of PEM fuel cells with 24-hour on-site hydrogen storage, its CAPEX is 108% to 163% higher than Tier 4 diesel generators. At 24 hours of runtime, PEM fuel cells are around 70% to 74% less expensive than lithium-ion batteries. PEM fuel cells scale better over longer run-times as they have separate power (fuel cell stack) and energy components (hydrogen storage). Future cost optimizations predict that PEM fuel cell systems will come down in price for both the

33 *CARB's Pathways Technical Support Documentation*, Table F.3 p.37, for gaseous green hydrogen (HYER): 10.51 gCO_2e/MJ of hydrogen produced, 120MJ of hydrogen = 1 kg of hydrogen. Assuming PEM fuel cell efficiency of 48%, PEM fuel cell consumes 67 kg to produce 1 MWh of electricity

34 *PEM fuel cell Life Cycle Analysis study*, Table 8, GWP value of 1kWe Unit

fuel cell stack and hydrogen storage (and fuel). The fuel cell stack itself is expected to be reduced to half its price within the foreseeable future.

OPEX – Hydrogen production is not as widespread compared to other fuels. It's the most expensive fuel of those evaluated in this paper. Globally, production cost for grey hydrogen ranges from around $1 to $3 per kg while green hydrogen ranges from $3 to $7.5 per kg[35]. As a result, fuel cost for this technology ranges from $245 to $379 per MWh for grey hydrogen (11% to 20% more expensive than diesel) and from $379 to $680 per MWh for green hydrogen (71% to 115% more expensive than diesel)[36]. Like the PEM fuel cell stack, there are initiatives to further reduce hydrogen production costs. USA's Department of Energy's Hydrogenshot initiative has a target of reducing green hydrogen production costs to $1/kg within the decade – bringing it to parity compared to grey hydrogen. The annual maintenance cost for a PEM fuel cell system is slightly lower than for diesel generators.

Other characteristics

Footprint – The size depends heavily on the type of hydrogen storage system used – liquid hydrogen or gaseous hydrogen, above-ground or underground. Liquid hydrogen, stored at cryogenic temperature (-253°C, -423°F), has a smaller footprint and lower delivered hydrogen cost but requires a vaporizer and more constant replenishment due to boil-off. Gaseous hydrogen requires a larger footprint and is more expensive, yet it does not require a vaporizer and no boil-off to manage. Subject to the amount of hydrogen needed for backup power and footprint constraints, there seems to be a cross-over point at which liquid hydrogen storage becomes economically more feasible than gaseous hydrogen storage. 24 hours of runtime at 1 MW requires on-site storage of around 2,000 kg of hydrogen. Hence, the footprint ranges from around 93 square meters (1,000 sq. ft., above-ground, liquid hydrogen storage) to 121 square meters (1,300 sq. ft., above-ground, gaseous hydrogen) per MW. This is 745% to 1,000% bigger than diesel generators. There are emerging, geographical independent underground hydrogen storage options, which could significantly reduce the footprint of the full solution.

Fuel availability – Hydrogen also has the most limited fuel availability. As of 2021, global annual production is around 120 million tons, primarily grey hydrogen produced from natural gas and coal[37]. This translates to around 13 quadrillion BTU, 78% lower than diesel's fuel availability. Scaling up green hydrogen production is currently under development. Significant investments are being announced.

Start-up duration – Depending on its configuration, PEM fuel cell stacks take approximately 60 seconds to go from off to 100% capacity, due to mechanical and thermal components of the fuel cell stack. However, system architectures offer an inverter module, which includes a relatively small battery. Bridging this gap with a battery lowers the start-up duration to less than 10 seconds, no difference from diesel and natural gas generators. Furthermore, due to concerns of response and subjecting PEM fuel cells to load changes, the battery is also used to manage step loads.

Evaluation summary

Table 7 summarizes how the 3 alternative technologies compare to diesel generators as the baseline technology. Light green shaded cells mean the technology performs better than diesel generators. Yellow shaded cells mean the technology

[35] IEA, *Future of Hydrogen report*

[36] Argonne National Laboratory, *System Level Analysis of Hydrogen Storage Options*, slide 6, delivery cost of hydrogen, $2.65/kg, assumes 48% PEM fuel cell efficiency: consumes 67 kg of hydrogen/MWh

[37] IRENA, *Green Hydrogen - A Guide to Policy Making*, p.6

performs the same or worse within a 30% margin. Red shaded cells mean the technology performs worse by a margin greater than 30%.

Table 7

*Summary of evaluated technologies' characteristics. *unlike the other technologies, lithium-ion BESS only has 4.7 operating hours/year (no monthly load testing)*

Characteristics for 24 hours of autonomy, 16.7 operating hrs/year	EPA Tier 4 diesel generator	Natural gas generator (rich burn)	Lithium-ion BESS*	PEM fuel cell w/ green hydrogen
Air quality (kg/MW)				
Annual NO_x emissions	11.2	0.53	0	0
Annual PM emissions	0.50	0.05	0	0
GHG emissions (kgCO_2e/MW)				
Annual Scope 1	11,924	10,638	0	0
Annual fuel production	4,325	3,907	1,844	1,411
Embedded carbon	22,000	26,400	1,224,000	112,000
Cost ($/MW)				
CAPEX	$800K - $1,200K	$1,000K - $1,300K	$7,000K - $9,500K	$2,100K - $2,500K
Annual fuel cost	$3,691 - $5,294	$1,887 - $1,937	$545 - $658	$6,329 - $11,356
Annual maint. cost	$9K - $10K	$9K - $10K	$34K - $46K	$8K
10-year TCO[38]	$885,158 - $1,302,624	$1,073,053 - $1,380,098	$7,231,800 - $9,813,079	$2,196,149 - $2,629,880
Other considerations				
Footprint (m²/MW)	11	30-32	111-139	93-121
Start-up duration (sec)	<10	10-45	<0.1	10-60

Based on Table 7, we can make the following conclusions:

- While all the technologies perform better in terms of direct emissions when they're operating, none perform better than diesel generators in all aspects.
- Out of these technologies, natural gas generators are the most feasible solution as they are comparable to the Tier 4 diesel generators with respect to CAPEX, footprint, and start-up duration. They offer a modest reduction in GHG emissions and significant reductions in fuel costs, PM and NO_x emissions. Although they are initiatives underway to run natural gas generators on hydrogen or hydrogen blend, today they still use fossil fuels. Thus, to some stakeholders, it is only an incremental improvement to diesel generators, especially to those with net-zero commitments.
- For a 24-hour resiliency application, lithium-ion BESS are the least feasible option due to the order of magnitude higher CAPEX, annual maintenance cost, and embedded carbon, despite the lack of direct emissions. Lithium-ion BESS are more viable for applications shorter than 4 hours of runtime.
- Out of the non-emitting options, PEM fuel cells are then the most feasible choice, especially with expected reduction in both CAPEX and fuel cost. Also, while it has significantly higher embedded carbon, running it for around 2 years (34 operating hours total) would lead to a lower emission profile

[38] TCO calculated with 8% interest rate. 10-year basis chosen as that's the expected lifetime of the lithium-ion BESS, which is the shortest of the evaluated technologies.

compared to natural gas generators. However, its high OPEX, maintenance cost in particular ($8,000/MW), relatively large footprint, and currently limited green hydrogen supply and delivery infrastructure may be barriers to their broad adoption in the near future. Even if there is an increase in hours (up to a total of 100 operating hours per year) of needed backup power (either due to above average outages, added site maintenance, or demand response program participation), it will still take diesel generators around 15 years to emit the same amount of GHG emissions as the cumulative GHG emissions of 24-hours lithium-ion BESS. Against the PEM fuel cells operated with green hydrogen and at 100 hours per year, GHG emissions will be on parity with diesel and natural gas generators in just over one year.

Diesel and natural gas generators, and PEM fuel cells have an expected lifetime of 20 or more years. Lithium-ion batteries, however, only have a design life of 10-15 years. Hence, assuming these assets are in operation for 20 or more years, the combined GHG emissions profile is most favorable for PEM fuel cells fueled by green hydrogen.

As mentioned before, these technologies are only a few of the alternatives to diesel generators for this application. It is also worth noting that replacing diesel generators with a sustainable alternative is only one aspect of data centers journey to reduce greenhouse gas emissions. Other technologies and considerations are outlined and explored in Appendix 2.

Conclusion

For a strict backup power application, there is no single technology that proves to be a clear successor to diesel generators. As of 2021, natural gas generators are likely to be one of the most feasible choices. With only a slight cost and footprint premium, they offer significant improvements in sustainability. Cleaner fuel alternatives (detailed in Appendix 2), such as biodiesel, renewable diesel (e.g., HVO), and renewable natural gas, are also realistic options, if they become more widely available. Yet, these alternatives may be viewed by some as too incremental.

Out of the two non-emitting technologies, PEM fuel cells are a more viable option relative to lithium-ion BESS when 24 hours of runtime are required. This is due to PEM fuel cells' lower CAPEX and lower embedded carbon. Furthermore, they have a roadmap to significantly reduce both CAPEX and green hydrogen cost. Though to ensure greater availability, they require significant buildout of hydrogen supply and delivery infrastructure. Lithium-ion BESS are not a practical choice for 24 hours of runtime, due to higher CAPEX and significantly larger embedded carbon. It's more suitable for applications with less than four hours of runtime (ex. short duration outages, peak shaving, renewable energy integration). Thus, eliminating direct emissions from a backup power solution with a 1:1 diesel generator replacement is not as simple as it may appear. Perhaps a combination of different technologies can lead to more significant reductions in a data center's overall GHG emissions profile. For further exploration on this topic, please read White Paper 74, *Three Data Center Shifts for Accelerating Adoption and Impact of Alternate Backup Technologies*.

About the authors

Allegia Wiryawan is a Senior Systems Design Engineer at Schneider Electric. She evaluates and analyzes new trends and technologies relevant to data centers, specifically power system architectures and energy storage technologies. She also creates reference design packages for data centers showcasing new products from Schneider Electric. Allegia holds a Bachelor's degree in Electrical Engineering from Tufts University, with a minor in Computer Science.

Carsten Baumann is a Solution Architect helping clients with their Industrial IoT and Sustainability initiatives in the Commercial & Industrial and Data Center markets to achieve greater resiliency, achieve sustainability objectives, and create economic benefits. Prior, he supported the Consulting and Engineering community by advising on resource-optimized energy management solutions in the data center market. He offers nearly three decades of experience in the data center, broadcast, telecommunications, AV, and IT industry. His papers have been published in peer-reviewed journals and he frequently speaks at national and international venues.
Baumann, joined Schneider Electric in early 2012. He is an active member of iMasons and the Green G working group (Next G). Until 2018, he served as Treasurer and President on the board of AFCOM Southern California, was chairman for The Global Society for Asset Management (G-SAM). Baumann recently completed a program at MIT in Smart Manufacturing and holds an electrical engineering degree from the Theodor-Litt-Schule in Giessen, Germany.

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Appendix 1: Initial assessment of alternative technologies

When it comes to replacing diesel generators, there are a wide variety of alternative technologies (both emerging and proven) for long runtime backup applications. We break these alternatives into two categories: **power-producing technology**; and **fuel source**. We assess each of these categories across multiple criteria to choose the most viable alternatives for the more detailed evaluation.

Power-producing technology

The power-producing technology is responsible for generating the electricity. There are three subcategories to consider: engine, turbine, and chemistry.

- **Engine** technologies use a reciprocating engine, such as diesel and natural gas generators, and alternators to produce electrical power.
- **Turbine** technologies use either combustion or pressure to spin a turbine to generate electrical power. Examples of these technologies are combustion-based turbines and microturbines, compressed air energy storage, pumped hydro, and small modular nuclear reactor (SMR). Like engine-based technologies, the combustion-based turbines can use different fuels (ex. ammonia, natural gas) with the added benefit of cogeneration (using waste heat for facility's thermal processes).
- **Chemistry-based** technologies use chemical processes to generate electrical power. This can be broken down into three categories: electro-chemical batteries (e.g., lithium-ion battery energy storage systems (lithium-ion BESS)), fuel cells (e.g., proton exchange membrane (PEM)), and flow batteries (e.g., vanadium redox flow batteries (VRFB)).

In selecting from these alternative technologies, we used the following criteria:

- Has the same usage as the baseline diesel generator, i.e., standby data center backup power with 24-hours of run-time. This excludes technologies suited for prime power and grid defection, such as solid oxide fuel cells (SOFC).
- Has no on-site deployment constraints (e.g., doesn't depend on specific geographic features). This does not refer to regulatory and permitting concerns, which is out of scope for this white paper to simplify the analysis.
- Has technology maturity and a viable pathway to further innovations. This excludes technologies that are minimally deployed or still in R&D. It allows for technologies that reached widespread deployment in other industries (ex. PEM fuel cells in material handling applications).

Table A1 shows the different technologies assessed with the above criteria. Cells shaded in red indicate that the technology does not meet those criteria. As shown in the last column of the table, only **PEM fuel cells** and **lithium-ion BESS** meet all criteria and, as a result, were selected for further evaluation.

Table A1

Assessment of power producing alternatives

	Data center usage	On-site deployment constraints	Maturity/ innovation pathway	Chosen for further evaluation?
Engine genset	Backup power	None	Mature	Baseline
Natural gas microturbine	Prime power	None	Mature	No
Ammonia turbine	Prime power	None	In R&D	No
Proton exchange membrane (PEM) fuel cell	Backup power + Demand response (hours)	None	Mature – material handling	Yes
Compressed air energy storage	Backup power + Demand response (hours)	Yes – geographic for large scale storage	Mature	No
Solid oxide fuel cell (SOFC)	Prime power	None	Mature	No
Pumped hydro	Grid services (hours)	Yes – geographic	Mature	No
Small modular nuclear reactor (SMR)	Prime power	None	In R&D	No
Vanadium redox flow battery	Backup power + Demand response (hours)	None	Pilot projects	No
Lithium-ion BESS	Backup power + Demand response (hours)	None	Mature – various industries	Yes

Fuel sources

There are many fuel alternatives for backup applications. In selecting from these alternative fuels, we used the following criteria:

- Has energy density at least as good as diesel, as it impacts the overall physical footprint
- Has fuel availability similar to diesel
- Has CO_2 emissions profile lower than diesel as this is the main contributor to a site's Scope 1 GHG emissions and thus the primary emission target for reduction

Table A2 shows the different fuels assessed with the above criteria. Cells shaded in red indicate that the fuel does not meet those criteria. As shown in the last column of the table, only compressed natural gas and hydrogen perform better than diesel on two out of three criteria and are consequently used for further evaluations.

Based on Tables A1 and A2 above, we have two power-producing technologies that use hydrogen and natural gas as a fuel source: engine gensets and PEM fuel cells. Additionally, we have a technology that doesn't use any fuel: lithium-ion batteries. Hydrogen generators have a much longer start-up duration and currently serve mainly as a prime power generation source. To use natural gas for PEM fuel cells requires the addition of a reformer, increasing both CAPEX and fuel costs of the system. Hence, we focus our comprehensive evaluation on three systems: the natural gas generator, lithium-ion battery energy storage system (BESS), and proton exchange membrane (PEM) fuel cells paired with hydrogen. Appendix 2 provides more information on the power-producing technologies and fuels that were not selected.

Table A2

Assessment of different fuel sources

Fuels for reciprocating engine genset	Energy density (DGE)[39]	CO_2 Emissions profile (kg/MMBTU)[40]	Fuel availability	Chosen for further evaluation?
Diesel	1	73	High availability	Baseline
Biodiesel (B100)	0.93	19[41]	Medium availability	No
Renewable Diesel (e.g., HVO)	0.94[42]	25[43]	Low availability	No
Compressed natural gas (CNG)	0.16	53	High availability	Yes
Ammonia	0.4[44]	None	Low availability	No
Hydrogen	2.7[45]	None	Grey H_2: medium availability Green H_2: low availability[46]	No

Appendix 2: Other technologies and considerations

As mentioned previously, selected technologies are only some of the alternatives to diesel generators. There are a few other technology and fuel alternatives that were previously eliminated but are still of note, such as sustainable diesel alternatives. There are also non-technical considerations for backup power, specifically re-evaluating operational requirements for it.

Excluded fuels and power producing technologies

Biodiesel

A more sustainable alternative to conventional diesel is biodiesel. It is produced from vegetable and cooking oils, grease, and animal fats via the process of transesterification[47]. Biodiesel, depending on its source and blend, can reduce overall carbon emissions of diesel generators. While there's no substantive difference in CO_2 emissions when burning conventional diesel or biodiesel, there is a reduction when looking at the full lifecycle production and combustion[48]. From CARB's default 2021 carbon intensity, biodiesel CO_2 emissions are 72% lower than conventional diesel's. Using biodiesel also leads to a reduction of other emissions. According to the EPA, a 100%-blend biodiesel (B100) would lead to a nearly 50% reduction of PM emissions. At the same time, it would also lead to an increase of NO_x emissions by around 10%. However, higher blends of biodiesel (such as B100) are not a drop-in replacement as it may require modifications to the equipment and can cause performance issues[49]. It is also not as widely available as conventional diesel.

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[39] *Alternative Fuels Data Center Fuel Properties Comparison*, For energy density, we used diesel gallon equivalent (DGE), which divides the energy content of a fuel by the energy content of diesel.

[40] https://www.eia.gov/environment/emissions/co2_vol_mass.php

[41] Calculated as a 74% reduction from diesel based on U.S. Department of Energy.

[42] Neste, *Neste Renewable Diesel Handbook*, Table 4, p.19, using volumetric densities

[43] CARB default 2021 carbon intensity, calculated as 66% reduction based on renewable diesel value

[44] Ammonia - The Other Hydrogen, Calculated from energy density of ammonia given in Table 1

[45] A gallon of diesel is 3.3 kg of diesel, hence when comparing at the same mass of fuel, hydrogen is more energy dense than diesel. If comparing on volumetric basis, diesel is more energy dense than hydrogen.

[46] Grey H_2 refers to hydrogen produced from natural gas via steam methane reforming. Green H_2 refers to hydrogen produced from water via electrolysis powered by renewables.

[47] https://afdc.energy.gov/fuels/biodiesel_production.html

[48] https://www.eia.gov/energyexplained/biofuels/biodiesel-and-the-environment.php

[49] https://afdc.energy.gov/fuels/biodiesel_blends.html

Renewable diesel

Another sustainable alternative to regular diesel fuel is renewable diesel, such as hydrogenated vegetable oils (HVO). While renewable diesel uses the same feedstock as biodiesel, it uses a different chemical process to produce it. Like biodiesel, renewable diesel's carbon intensity depends on the feedstock used. CARB's default 2021 carbon intensity of renewable diesel is 66% lower than conventional diesel. Unlike biodiesel, renewable diesel does not require modifications to the equipment[50]. However, it is not as widely available as biodiesel, and certainly not as conventional diesel. By 2025, USA's annual renewable diesel production capacity is expected to range from 2 billion to 5 billion gallons (up from 1 billion gallons currently). This translates to less than 1 quadrillion BTU per year by 2025. Meanwhile, USA's annual production of conventional diesel in 2014 was around 10 quadrillion BTU.

Solid Oxide Fuel Cells (SOFC)

Besides PEM fuel cells, SOFC are another fuel cell technology that is of great interest; Bloom Energy has deployed 65 MW of their SOFC systems in data centers in USA. Most SOFC can be directly powered by natural gas as well as hydrogen, while PEM fuel cells require pure hydrogen to operate. SOFC have higher operating temperature compared to PEM fuel cells, thus they have a longer start-up duration. Due to these properties, SOFC systems have been primarily deployed to provide prime power and the electric grid is instead viewed as backup power. Due to this change in power architecture paradigm, while SOFC removes the need of diesel generators, they are not considered a drop-in replacement to diesel backup generators.

Flow batteries

Flow batteries are one of the technologies that were included in our initial considerations but were not selected for further evaluation. Like fuel cells, flow batteries are non-emitting resources with separate power (flow battery stack) and energy components (electrolyte tanks). This allows more cost-effective scaling of the system's runtime capacity, as one only needs to increase electrolyte tanks without increasing the flow battery stack. However, unlike fuel cells which can consume a continuous supply of hydrogen, flow batteries use a closed loop system. The duration of the flow batteries relies on the amount of electrolyte tanks and the time it takes to recharge it. The most common type of flow batteries is vanadium-redox, some of which have been deployed for pilot projects. Unlike PEM fuel cells and lithium-ion batteries, flow batteries have not been scaled up through applications in other industries, and thus are still a relatively immature technology.

Compressed air energy storage (CAES)

The idea of using compressed air to drive industrial processes has been around since the late 19th century and has been implemented in various cities around the world. This technology is like pumped hydro power plants, but instead of using water as a medium, it uses air as the storage medium. When storing energy, the system compresses either ambient air or another gas and stores it under pressurized conditions. It discharges by heating up the pressurized air and directing it to expand and move a turbine to drive a generator. This technology tends to have large nameplate capacity, in the hundreds of MWs. However due to the low density of air, it requires large volumes of air to be stored. Most economically feasible ones require storing the compressed air in suitable underground caverns.

Nuclear – small modular reactor (SMR)

[50] https://www1.nyc.gov/assets/dcas/downloads/pdf/fleet/NYC-Fleet-Case-Study-Renewable-Diesel-7-16-2020.pdf

More readily available information and federal funding suggest that advanced SMRs are a likely carbon-free energy production alternative in the future. SMRs seem to be well-suited for local energy generation in the 10+ MW range, where they are promised to be inexpensive with minimal safety risk. Yet, the US Office of Nuclear Energy lists that significant technology developments and licensing risk remain. According to their website, demonstration projects may materialize in the late 2020s or early 2030s.

Alternative data center operations

Outside of technology considerations, data centers can change their operational requirements for backup power. This could be due to a change in its direct environment (ex. utility grid becomes increasingly unreliable) or a change in criticality of IT applications performed in the data center (ex. IT applications supported by multiple data centers). The next sections are a brief look at these; White Paper 74, *Three Data Center Shifts for Accelerating Adoption and Impact of Alternate Backup Technologies* provides a more thorough evaluation on this topic.

Extended backup time requirements

With the advent of climate change related extreme weather events, extended backup run-time might be needed. For example, California has indicated that with Public Safety Power Shutdown (PSPS), backup times up to 96 hours may be needed. At these runtimes, most on-site fuel storage solutions are impractical. One can argue that multiple fuel sourcing contracts may be negotiated. However, in cases of severe weather events, disruptions to the fuel supply may co-exist. A combination of innovative technologies and backup strategies may be needed to meet these extreme requirements.

Non-backup power strategies

Various internet giants have acknowledged that there is an upper limit to the level of resiliency and availability a single data center can achieve. To achieve higher levels of availability, it requires having multiple data centers where data is replicated synchronously between them with an acceptable degree of latency, and far from each other so as avoid common cause failures (e.g., a storm or flood takes down both data centers). An example of this is Amazon's Availability Zones. Furthermore, as servers and IT loads become more differentiated, different applications have different uptime requirements. Thus, in case of an emergency, some loads can be shifted to another facility and the facility can have multiple technologies providing backup power but with different capacities and runtimes.