Decarbonized Resilience

Assessing Alternatives to Diesel Backup Power

PREPARED FOR

Enchanted Rock, LLC

PREPARED BY

Ryan Hledik

Peter Fox-Penner

Roger Lueken

Tony Lee

Jesse Cohen

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THE Brattle GROUP

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- Dr. Fox-Penner is an Academic Advisor to The Brattle Group and Chief Strategy Officer of Energy Impact Partners.

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I. Introduction

Improved resilience has emerged as a top priority for the U.S. power grid. Efforts to mitigate wildfire risk in Northern California last year led to hundreds of thousands of electricity customers being disconnected from the grid. During hurricane season, customers in the Eastern and Southern U.S. often face the associated threat of multi-day power outages. In many other parts of the country, portions of the local power grid are susceptible to interruptions due to a variety of other factors. Improved resilience would reduce or avoid those outages, allowing industries, businesses, and households to maintain their uninterrupted supply of electricity.

Resilience can be improved through the deployment of microgrids, among other options such as vegetation management and circuit hardening.[1] Microgrids have been described in a wide variety of ways. Simply put, the term "grid" refers to a combination of power generation, customers who consume the power, wires that deliver the electricity to customers, and a control system that manages this process. As discussed in this paper, a microgrid simply is a small, self-sufficient grid.[2]

Some types of microgrids provide resilience by serving load locally. If portions of the power grid are temporarily turned off to prevent wildfires or if a transmission line is taken offline during a hurricane, microgrids "downstream" of those interruptions continue to keep the lights on by providing power from local resources.

Parallel to the search for improving grid resilience is a strong focus among utilities and policymakers on a cleaner U.S. power supply, with goals to limit greenhouse gas (GHG) emissions and improve local air quality. Twenty-one utilities and 23 states have committed to massive reductions in electricity generation emissions – typically reductions of 80% or more - over the next 10 to 30 years.[3]

Thus far, diesel engines have been the primary source of power supply for systems designed to provide backup power and thereby improve grid resilience.[4] In many cases, those diesel generators are installed "behind the meter" of individual customers that require backup power supply in case of an interruption (e.g., hospitals or data centers). But utilities have deployed larger scale diesel

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1 Other effective methods for improving resilience include, for instance, undergrounding, sectionalizing, or expanding portions of the system of electric lines that deliver electricity to customers.

2 This definition is derived from a similar, relatable description provided by David Roberts and Alvin Chang, "Meet the microgrid, the technology poised to transform electricity," *Vox*, last updated May 24, 2018.

3 See www.c2es.org and www.sepapower.org, accessed May 19, 2020.

4 For the purposes of this paper, "diesel generator" and "diesel engine" refers to traditional diesel-fueled reciprocating internal combustion engines used for backup power.

generators on their systems as well, temporarily installing the generators at locations in the power grid that are more susceptible to interruption, or where the cost of interruption is very high.

Given goals for a cleaner U.S. power supply, utilities and policymakers may be seeking alternatives to a strategy of deploying diesel generators for backup power/resilience. As this report shows, as compared to BTM diesel generators as well as when they are deployed in community side applications, local resilience can be provided economically by microgrids that use renewable or pipeline natural gas, alone and in combination with solar and storage. Relative to diesel, these alternatives can virtually eliminate the emission of pollutants such as NOx, particulate matter, and volatile organic compounds, which contribute to local air quality problems. Additionally, natural gas generators have lower CO_2 emissions rates than diesel generators, while other options analyzed in this study could provide an entirely carbon-free replacement for diesel generators.[5]

Therefore, a critical question facing utilities, regulators, communities, large energy users, and other industry stakeholders is whether the same level of local resilience provided by diesel backup generators and/or microgrids can be achieved through alternatives that are more consistent with clean energy goals. The purpose of this report is to compare the feasibility, economics, and GHG emissions of several alternative microgrid systems commonly considered for resilience purposes.

II. Approach

Defining Resilience

Generally, the term "resilience" refers to the ability of the power grid to withstand and recover from events that otherwise would lead to power outages. Significant reliability events, such as hurricanes or interruptions to mitigate wildfire risk, can result in transmission-level outages. In these instances, a community-level microgrid solution deployed at the substation or mid-feeder can provide resilience to all downstream customers (i.e., hundreds to thousands of customers).

This paper focuses on microgrid solutions that could provide 100% reliability to all load served by a representative distribution substation in Northern California for two to four consecutive days. Those effectively are the resilience criteria established by PG&E in Request for Offers (RFO) for resilient microgrids released earlier this year.[6] Given the range of ways in which resilience requirements could be defined, the PG&E RFO was used as the basis for this study's definition because it is a tangible example of how one utility has chosen to define resilience in practice. While the analysis is based on market conditions in California, many aspects of our analysis apply elsewhere in the U.S., making the findings relevant beyond California's borders.

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5 See Technical Appendix for additional detail on emissions rates.

6 PG&E, "2019 System Reliability Request for Offers, Distributed Generation Enabled Microgrid Services Phase, Solicitation Protocol," December 11, 2019.

Resilience microgrids are designed to ensure electricity supply for a variety of outage types and durations. Outage durations can range between momentary "blips" and months-long interruptions. Similarly, some outages occur with no advance notice while others (such as those from wildfires public safety shutoffs) can occur with advance warning. This report focuses on outages similar to those highlighted by the PG&E RFO (i.e., outages that last up to four days). Additionally, we assume that there would be several hours of advance notice of a potential resilience event. This would reflect, for example, the ability to anticipate with at least several hours of notice weather conditions related to events such as hurricanes or wildfires. Although the natural gas and renewable natural gas (RNG)[7] microgrid options in this study can perform without advance notice for any length of outage, these outage parameters are important for evaluating hybrid microgrid systems that include solar and storage.

Of course, there are other ways resilience could be defined. Key factors in the definition of resilience include the predictability and duration of the outage event, and the desired level of reliability during the outage event. For example, not all outages can be predicted with several hours of advance notice. Animals are a remarkably common cause of distribution outages and tend not to provide notification before disrupting the power system. Additionally, certain resilience objectives may be met by providing less than 100% reliability to all load. For instance, residential customers may wish to install behind-the-meter generation that powers only critical end-uses (e.g., lighting, garage doors, wifi, and refrigeration). Or customers may be willing to accept the risk that some but not all outages would be mitigated, depending on circumstances surrounding the outage. A useful extension of this research would be to evaluate alternative definitions of resilience beyond the definition used in this paper, along with the microgrid configurations that best address those reduced requirements.

Microgrid Configurations Analyzed

This study evaluates four microgrid options that are often considered as alternatives to diesel generators used in microgrid applications. Additional detail on the operational characteristics of these options is included in the attached Technical Appendix.

- *Natural gas generator:* The natural gas engine modeled in this study is a rich burn natural gas reciprocating engine capable of maintaining utility-grade voltage and frequency levels when in islanded mode.[8] It is assumed to be connected directly to the utility's gas

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7 RNG, also sometimes referred to as biogas, consists primarily of methane and typically is derived from organic waste material. Sources of RNG could include, for example, dairy farms or landfills.

8 Alternative technologies, such as natural gas turbines that are capable of maintaining voltage and frequency levels when in islanded mode, would also be possible.

distribution system at the substation level and receives its fuel from a local gas distribution utility.[9]

- *Renewable natural gas (RNG) generator:* The RNG engine is based on the same generation technology as the natural gas microgrid, but is fueled by RNG. We have assumed that RNG would be injected into the gas distribution system in a quantity equal to the fuel needs of the microgrid; the generator is not assumed to be directly connected to an RNG supply through a dedicated pipeline.[10]

- *Community-scale solar-plus-storage:* The solar-plus-storage microgrid analyzed in this study is a ground-mounted solar PV facility with an AC-tied lithium ion battery located on-site. A broad range of solar and storage configurations were considered, with the solar-to-storage capacity ratio ranging from 0.25-to-1 to 4.0-to-1, and the maximum discharge duration of the battery ranging from 2-hours to 8-hours.

- *Community-scale "hybrid" system:* The hybrid microgrid is a three-resource system, including an RNG engine, a solar PV facility, and a battery, all with the characteristics described above.

Further extensions of the research could include an assessment of fuel cells or solar and storage distributed widely along the system's feeder, in front of or behind the customer meter.

Modeling Overview

Each microgrid option is designed with the primary objective of providing fully adequate and uninterrupted power for four days to a representative 10 MW substation in Northern California.[11] At times when the microgrid is not used to mitigate an outage or held in reserve in anticipation of a potential outage, it is assumed to have the ability to earn wholesale market revenues consistent with current CAISO market rules. This includes revenue from contracts to provide the grid operator with resource adequacy (i.e., capacity value), as well as revenues from selling energy into the CAISO day-ahead and real-time energy markets.

The analysis identifies the sizing and configuration of each microgrid option that minimizes the total net cost of the microgrid (i.e., capital and operating costs less market revenues) while satisfying the previously-described resilience criteria. The GHG emissions impact of each microgrid option is calculated based on the resulting configuration and associated operation of the microgrid.

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9 Other forms of natural gas or RNG delivery are possible; this study examines only delivery by a gas distribution system.

10 This is consistent with the approached proposed by PG&E in its microgrid RFO.

11 Representation of substation load accounts for hourly load patterns observed in Northern California.

The Brattle Group's MiRiAD[12] model was used to analyze feasibility, economics, and GHG emissions impacts of each of the microgrid options. The MiRiAD model addresses several challenging aspects of microgrid assessment, including:

- Sizing and design decisions that can account for a wide range of possible system conditions and resilience goals, as well as weather-driven relationships between load and solar output;
- Market dispatch decisions that account for operational constraints of the microgrid associated with dispatching against market prices with imperfect foresight; and
- GHG accounting that includes the lifecycle emissions impact of the microgrid.

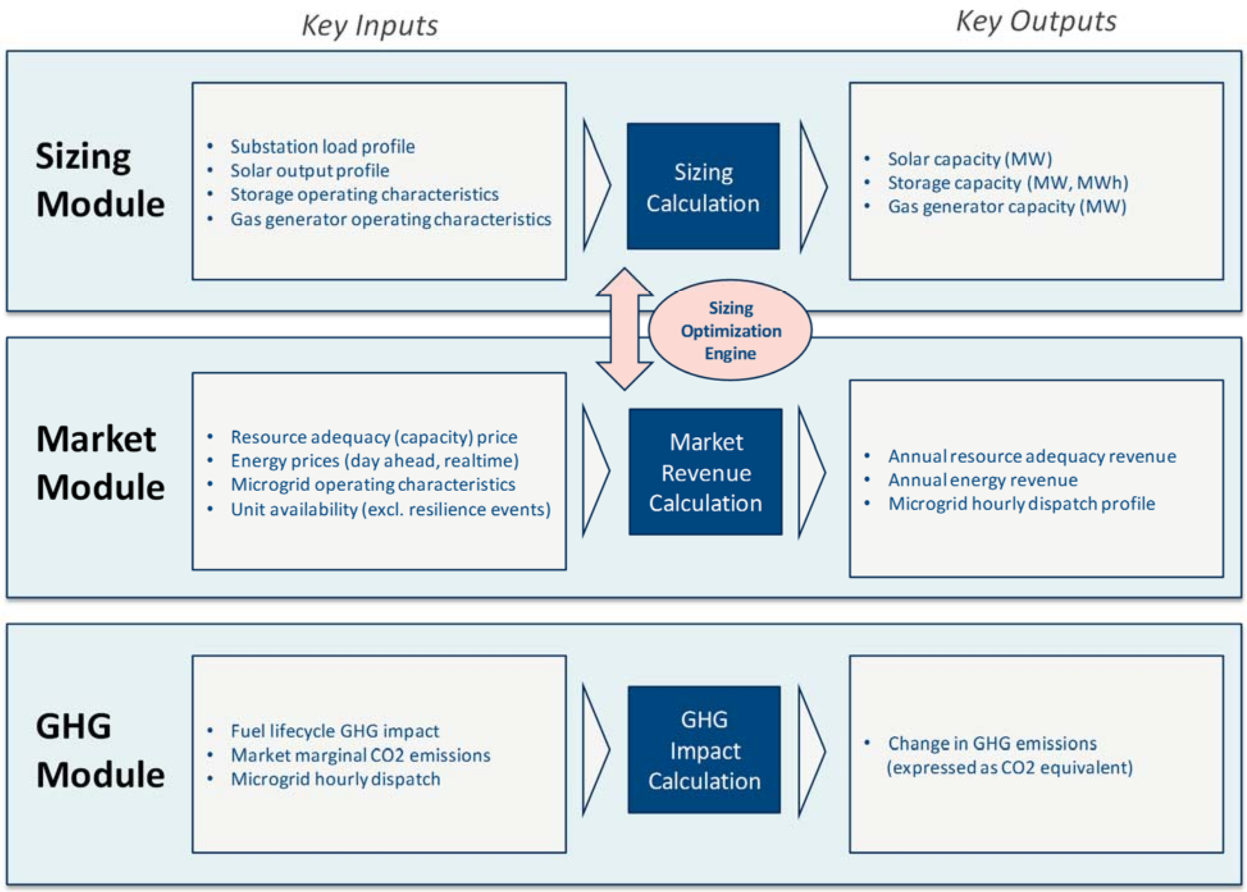
A summary of the MiRiAD modeling framework is provided in Figure 1; more detail on the modeling approach can be found in the Technical Appendix.

This study's economic evaluation of the microgrid options uses the traditional measures of the net present value of capital and operating outlays and market revenue streams over the assumed system lifetimes, which is 30 years for all options. A weighted average cost of capital of 8% is used as the discount rate. This approach implicitly assumes that all the options examined are financeable by the market under these terms. While this may not be the case for certain systems in certain locations, the microgrid has matured to the point where economic comparison on this basis are reasonable and informative to stakeholders.[13]

12 Microgrid Resilience Assessment and Design

13 For example, some locations or technology options may face permitting costs or risks that render them infeasible. As one example, we discuss space constraints and land costs for solar systems further below.

Figure 1: MiRiAD Modeling Framework



Source: The Brattle Group.

Note: Applicability of individual inputs and outputs shown depends on type of microgrid being analyzed.

Microgrid Costs

Capital costs, operating costs, and operating characteristics of the solar-plus-storage microgrids were based on a review of publicly available data, primarily from the National Renewable Energy Laboratory (NREL). Capital costs, O&M costs, and operating characteristics of the gas microgrids were provided by Enchanted Rock, while fuel costs were based on a review of PG&E gas delivery charges as well as publicly available commodity cost estimates. Additional detail on cost assumptions is provided in the Technical Appendix.

Market Revenues

This study quantitatively accounted for revenues that could be earned by the evaluated microgrid options in the CAISO energy market, as well as by providing resource adequacy (RA).

CAISO energy market prices were based on a Brattle simulation of the California power system in 2028. This reflects the expectation that there will be significantly larger amounts of renewable generation and storage deployment than are observed in the market today. Hourly day ahead energy prices were simulated using Power System Optimizer (PSO), a production cost model with nodal representation of the entire WECC. Additional revenue associated with the ability to redispatch the microgrids into the 15- and 5-minute real-time energy markets was based on simulated dispatch of the resources against recent historical CAISO market prices.[14]

The resource adequacy (RA) price is based on data published by the California Public Utilities Commission (CPUC) reflecting the results of recent RA contracts in California. The analysis does not forecast changes that may impact RA prices in the future, attributable to developments such as once-through-cooling related retirements of gas units or increases in the amount of storage that will come online. Given that RA prices could trend either upward or downward over the modeling horizon due to these and other market shifts, this study adopts a simple assumption of stable RA prices at current levels.

In addition to energy and RA value, it is possible that certain microgrid configurations would be awarded renewable energy certificates (RECs), which would provide another revenue opportunity. Under current rules in California, an RNG generator would need to meet various eligibility requirements related to the nature of its contract for RNG supply and demonstrating that the RNG producer had not already been awarded RECs for producing the fuel. Given the nuanced nature of REC accounting in this context, and significant uncertainty in the future price of RECs in California, this additional potential revenue stream has not been quantified in this analysis for any of the microgrid options.

Additional detail on market price assumptions and Brattle's methodology for dispatching the microgrid systems against those prices is provided in the Technical Appendix.

GHG Emissions

This study quantifies the GHG impacts of each analyzed microgrid option.[15] The microgrid options can impact GHG emissions in two different ways. First, when being dispatched into the CAISO energy market, they displace generators that otherwise would have run. The emissions of these "marginal" generators are avoided due to output from the microgrids.[16] The marginal emissions rate of generation was estimated based on a review of the results of the CAISO market simulation described above. In California, over the course of a year the marginal generation emissions rate is determined by a blend of output from natural gas generators and renewable generators.

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[14] Ancillary services revenues were also considered, but not modeled due to an expectation that there would be limited incremental revenue potential beyond that earned through sub-hourly real-time redispatch in the energy market over the 30-year forecast horizon.

[15] For a comparison of emissions rates of other emissions sources, such as NOx, volatile organic compounds, and particulate matter, see the Technical Appendix.

[16] The simulated CAISO energy prices used in this study reflect the cost of allowances in California's cap-and-trade program, serving as a financial representation of a portion of the CO_2 impacts of the microgrids that are discussed later in this paper.

The fuel combustion by the microgrid generators (if any) also impacts GHG emissions. GHG emissions of the gas generators are calculated on a "lifecycle" basis. This accounts for the GHG emissions associated with burning the fuel at the generator as well as for the net GHG impact of producing and delivering the fuel. As is discussed later in this paper, the use of RNG can reduce GHG emissions on a lifecycle basis, if it results in methane being converted to less-potent CO_2 rather than being released directly into the atmosphere. Solar PV does not burn fossil fuel and, under the assumptions of this study, storage charges almost exclusively from the co-located solar facility, so solar-plus-storage generators do not contribute to GHG emissions in this manner.

III. Findings

Our analysis concludes that three of the four evaluated technology options are economically and technically feasible for resilience purposes: Natural gas generator microgrids, RNG generator microgrids, and "hybrid" systems that include solar, storage, and an RNG generator.[17] The results show that natural gas generator microgrids provide the most attractive economics, while the addition of solar and storage to an RNG microgrid can meaningfully reduce net costs of the system where sufficient land is available.[18] As explained further below, while standalone solar-plus-storage systems have a highly positive outlook as bulk system resources for providing value in the CAISO market, microgrids running *only* on solar and storage are effectively infeasible for distribution system applications requiring 100% reliability over four consecutive days.

Results of the economic analysis for each feasible microgrid option are shown in Figure 2. As discussed further below, two cases were analyzed for the hybrid microgrid option, reflecting different assumptions about the amount of land that would be available for installing the solar PV portion of the facility. The first case assumes a 4-acre land constraint (with 1 MW of solar capacity), and a second assumes a 20-acre land constraint (with 5 MW of solar capacity).

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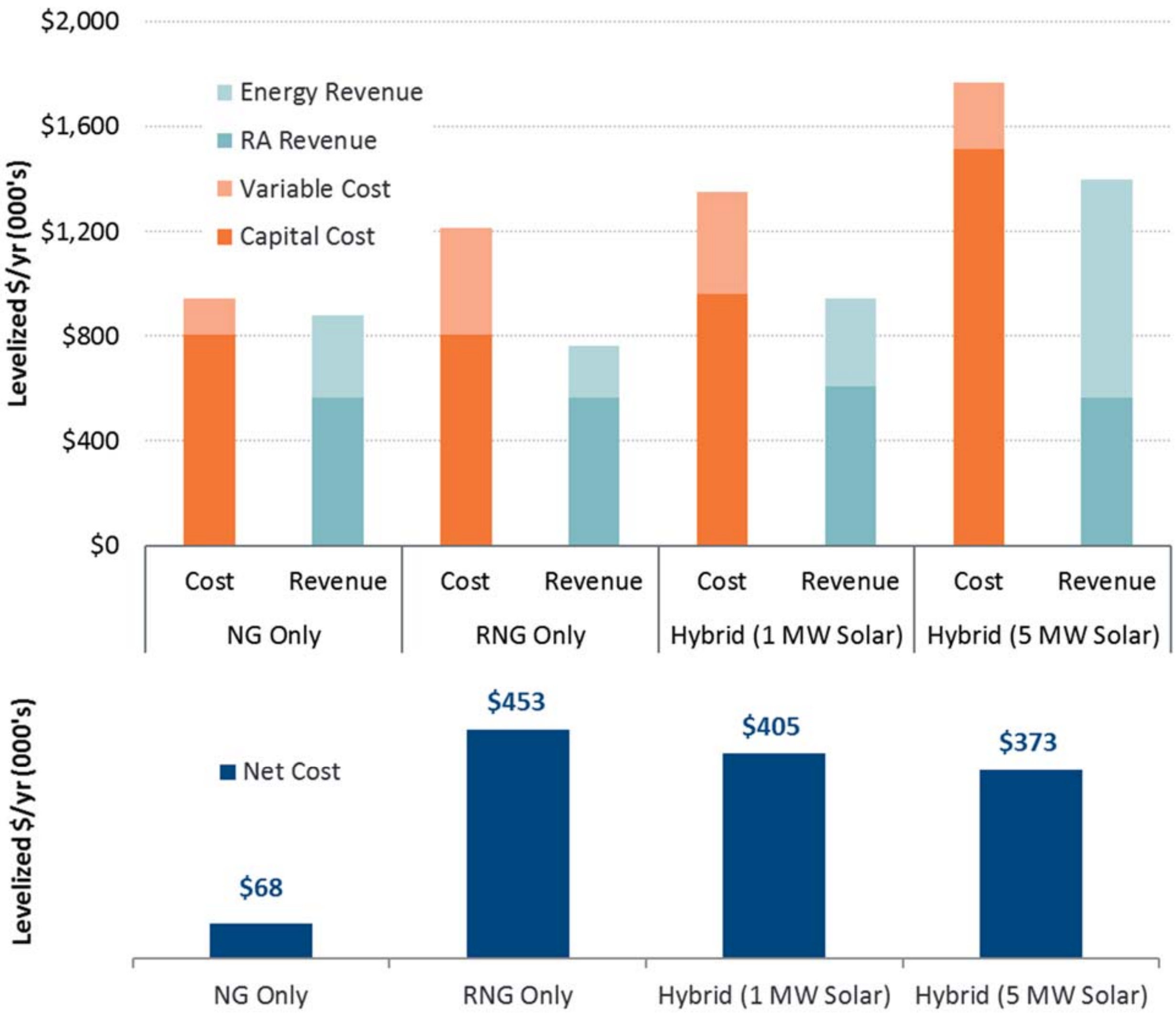
[17] Two versions of the hybrid system were modeled: one reflecting a 4-acre land constraint, and a second reflecting a 20-acre land constraint.

[18] In the figure, positive net costs represent the remaining cost of providing the required level of resilience, as defined in this study, for each microgrid option.

Figure 2: Microgrid Revenue and Cost by Configuration



Note: Results shown are for a 10 MW distribution substation. Hybrid system with 1 MW solar includes a 1 MW / 4 MWh battery. Hybrid system with 5 MW solar includes a 5 MW / 20 MWh battery.

Natural Gas Generator

Advantages of gas engine microgrids can include a minimal physical footprint, quick installation times, near-instantaneous response times, and virtually no operational constraints (e.g., no minimum run times and extremely fast ramp rates). Under the assumptions in this study, the capital and operating costs of the natural gas microgrid are roughly offset by its market revenue potential. In other words, the natural gas microgrid could nearly break even over its lifetime, in addition to providing highly valuable resilience to a local distribution substation. This market value is driven by the ability of the generator to provide resource adequacy and also to operate flexibly in CAISO's energy markets, arbitraging between the day-ahead and real-time markets. The generator can thereby earn significant energy market revenues while running for relatively few hours of the year.

In particular, the dispatch simulations in this study indicate that the natural gas generator would run for only about 275 hours of the year (i.e., 3% of hours), including when the generator runs for resilience purposes.[19] On an annual basis, this low capacity factor means that natural gas microgrid GHG emissions are modest compared to those of gas units that are built for the primary purpose of continuously selling into the CAISO markets (e.g., large scale combined cycle units, which can run at a capacity factor of up to 85%).[20] On an annual basis, the lifecycle GHG emissions of the 10 MW gas generator would amount to 1,700 tonnes of CO_2 per year, or the equivalent of 370 cars on the road. A fleet of 500 MW of natural gas microgrids operating in a similar manner would have a carbon footprint equal to 0.002% of PG&E's total carbon footprint in 2018.[21]

Many states and utilities are focused on decarbonizing the economy by transitioning away from fossil fuels. As such, a possible concern raised by some stakeholders could be that, despite low capacity factors and a small GHG footprint, gas microgrids will prolong the economy's dependence on gas infrastructure. However, the extremely low fuel consumption by natural gas microgrids will have an inconsequential impact on natural gas consumption in California. For instance, if 500 MW of natural gas microgrids were deployed for resiliency, their annual gas consumption would equate to only 0.0003% of statewide total gas consumption in 2018. From this standpoint, natural gas microgrids should not materially impact California's decarbonization/degasification goals.

RNG Generator

RNG generator microgrids offer most of the same benefits of natural gas generators, as described above. They are identical small, highly flexible resources with relatively low capital costs, simply fueled from a different gas source. Since RNG fuel costs more than natural gas, RNG generator microgrids run even less frequently and yield less energy market revenues than natural gas generators, while still accruing resource adequacy revenues. As such, market revenues fall short of the costs of RNG-based systems under the assumptions in this analysis.

The key differentiator between RNG generators and natural gas generators is their GHG impact. Whereas natural gas generators have marginally positive GHG emissions (as discussed above), on a lifecycle basis, RNG generators can actually *reduce* total global GHG emissions. How does this work? RNG is composed primarily of methane, which is captured from facilities like landfills and dairy farms. If not for the decision to capture the methane, it otherwise would be released into the atmosphere, contributing significantly more to global warming than CO_2 on a per-unit basis.[22]

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19 As discussed in the Technical Appendix, the generator is assumed to run for one 96-hour reliability event and two 48-hour reliability events. The generator runs infrequently in the energy market primarily due to relatively high variable costs.

20 CAISO, "2018 Annual Report on Market Issues and Performance," May 2019.

21 PG&E Website: http://www.pgecorp.com/corp_responsibility/reports/2019/en02_climate_change.html

22 The methane may also be burned, or flared, onsite, which also produces CO_2. Using the EPA's "Emission Factors for Greenhouse Gas Inventories," a ton of methane makes the same contribution to global warming as 25 tons of CO_2. See EPA "Emission Factors for Greenhouse Gas Inventories," available at: https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf.

By burning the captured methane in a generator and converting it to CO_2 as a result, GHG emissions can be reduced relative to the baseline scenario in which the gas is not captured or flared. Ultimately, as the discussion indicates, the GHG impacts of RNG depend on the source of the RNG and assumptions about emissions in the absence of RNG production. We discuss these assumptions in more detail in a later section of this paper.

Community-Scale Solar-plus-Storage

Standalone *utility-scale* solar-plus-storage projects currently have a positive economic outlook in California. Such projects benefit from recent substantial declines in technology costs, additional cost savings attributable to the Federal Investment Tax Credit (ITC) and the ability to provide year-round clean energy and RA value. The significant share of solar-plus-storage projects in the CAISO interconnection queue (amounting to 40% of all capacity in the queue) is one indicator of the positive market outlook for solar-plus-storage as a bulk system resource in CA. Accordingly, Southern California Edison recently announced the completion of seven contracts for 770 MW of battery storage, much of which will be co-located with solar facilities. PG&E recently proposed over 400 MW of storage projects that would bring the total size of the utility's storage portfolio above 1,000 MW.

However, based on the assumptions in this analysis, standalone solar-plus-storage is extremely constrained as a solution for providing 100% reliability to distribution substations for four consecutive days. In this analysis of a prototypical 10 MW substation, in order to provide 100% reliability a solar-plus-storage facility would require more than 20 MW of solar PV capacity and a battery with storage capability of around 90 MW and 350 MWh (i.e., one of the largest batteries to be deployed in the U.S.).[23] Such a project would require over 90 acres of land. These land requirements are an order of magnitude greater than the largest land availability observed near "at risk" substations in PG&E's Northern California service territory.

Several additional considerations also significantly constrain the feasibility of standalone solar-plus-storage as a 100% reliable distribution microgrid option. These considerations include:

- The project would require advance notification of a reliability event in order to ensure that the battery was fully charged entering the event. Such advance notification is feasible for some but not all types of distribution outages.
- The large-capacity solar-plus-storage system would need to be connected to the transmission side of the substation and the associated electrical engineering would need to allow for a high-capacity transmission-level interconnect and disconnect. The associated cost of the necessary interconnections and transmission reinforcements could be significant.
- The system operator would need to study the solar-plus-storage system and waivers would be required to "jump the queue" in order for the microgrid to come online quickly, or even

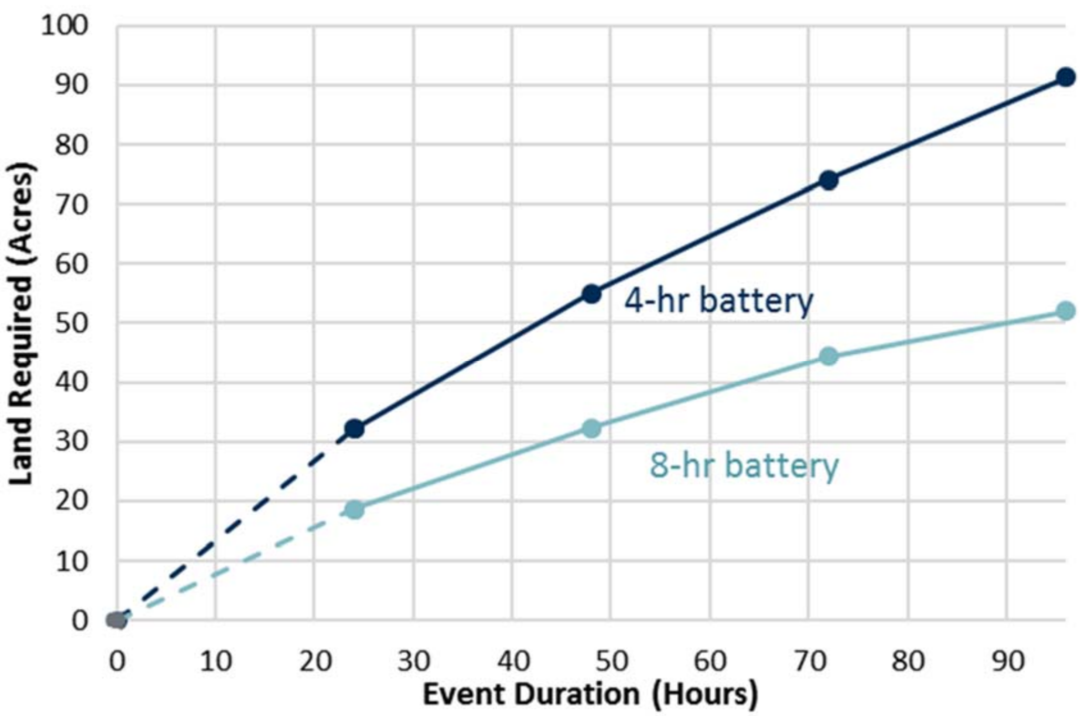
23 The combined 20 MW of solar capacity and 90 MW of storage capacity is reported as net of any n-minus-1 contingency capacity.

in a matter of years. Alternatively, the project simply would have to wait its turn in the queue.

- The project would need to be located very close to the distribution substation that requires resilience support. This can create unique siting challenges and presents the risk that costly upgrades or mitigation would be required as a permitting condition.
- Developers would need to be able to finance the large solar-plus-storage merchant facility (or secure an off-taker) on the strength of projected energy market and RA revenues, in spite of these risks and uncertainties. Given the large solar-plus-storage capacity necessary to provide the required level of resilience for just a single distribution substation, deploying such projects to satisfy a significant portion of California's resilience needs would erode additional RA revenue opportunities.

As such, the conditions under which standalone, community-scale solar-plus-storage could provide 100% reliability as a distribution microgrid are, at best, extremely highly constrained. The ability of solar-plus-storage to meet 100% reliability requirements potentially could be improved if the resilience requirement were for a duration of significantly less than four consecutive days. However, according to the modeling in this study, providing 100% reliability for even just a single day would require land availability of 20 to 30 acres, depending on the duration of energy storage capability in the battery. Figure 3 summarizes the relationship between reliability event duration and land requirements for solar-plus-storage microgrids with 4- and 8-hour batteries.

Figure 3: Solar-plus-Storage Land Requirement, as a Function of Outage Event Duration



Note: Assumes 1-to-4 solar-to-storage capacity (MW) ratio. Dotted line indicates extrapolation to zero.

It is clear that utility-scale solar-plus-storage will continue to be developed in California and elsewhere for its significant value as a bulk power market resource. However, its ability to serve as a standalone distribution-system-specific resilience solution is extremely constrained under the conditions analyzed in this study.

Community-Scale Hybrid System

A "hybrid" system would combine solar, storage, and a gas generator, with each element sized to optimize the overall economics while still meeting all resilience requirements. Such a system could take advantage of both the positive economics of solar-plus-storage and the footprint-minimizing benefits of the gas generator. This scaled-down approach could potentially avoid the challenges discussed above for standalone solar-plus-storage systems as a microgrid solution.

Where feasible, an economically beneficial system would maximize the size of the solar-plus-storage facility on the distribution grid, subject to land and other technical constraints. A gas generator would be sized to provide the remaining required level of reliability.

This study has considered two different hybrid designs, reflecting different illustrative assumptions about the amount of affordable land available for the solar-plus-storage component. The first case assumes 4 acres of land availability, which could accommodate roughly 1 MW of solar and a 1 MW / 4 MWh battery.[24] An additional 9.7 MW gas generator would address the remaining reliability requirement. The second case assumes 20 acres of land availability, which results in a system with capacity that is allocated roughly evenly between solar (5 MW), storage (5 MW / 20 MWh), and gas (5 MW). In both cases, the gas generator was assumed to be fueled by RNG in order to provide insight regarding the extent to which the addition of solar-plus-storage could improve the economics and environmental benefits of an RNG-only system. Similarly, a natural gas generator could be combined with solar and storage to improve environmental benefits.

The inclusion of solar-plus-storage meaningfully reduces the net cost of the RNG microgrid, though not to the point of near-breakeven economics observed for the natural gas microgrid. Solar-plus-storage improves the environmental benefits of the RNG microgrid as well, due to the daily output of carbon free electricity from the solar-plus-storage facility.

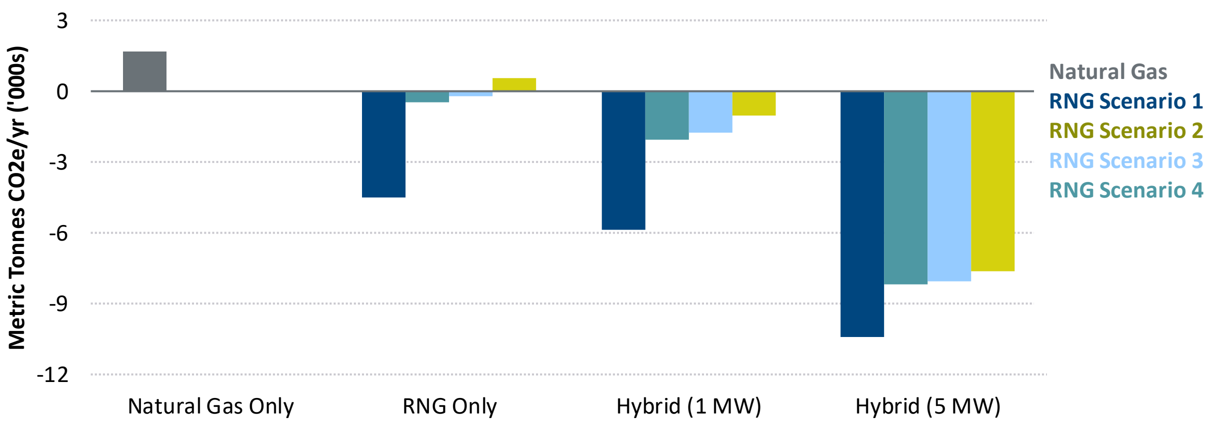
IV. GHG Analysis

The microgrid options analyzed in this paper can impact GHG emissions in three ways: by displacing marginal generators that otherwise would have run in the CAISO market, by displacing the emission or flaring of methane converted to RNG, and by burning fuel. As described above, a natural gas generator used in a resilience microgrid would marginally increase GHG emissions

24 The analysis points toward solar-plus-storage configurations with a 1-to-1 solar-to-storage capacity ratio and a 4-hour battery as approximately balancing the tradeoff between land requirements and economic attractiveness.

relative to a case where no new microgrid solutions were deployed (i.e., customer outages). An RNG-burning, otherwise similar generator and hybrid systems that include solar and storage have the potential to reduce GHG emissions in this context. Figure 4 summarizes the annual GHG impact of each feasible microgrid option analyzed in this study. The annual GHG emissions are expressed on a net lifecycle basis in terms of CO_2 equivalent (CO_2e), and are relative to a case where no new resilience measures are deployed.[25]

Figure 4: Microgrid Lifecycle GHG Emissions, by Configuration



Note: Results shown are for a 10 MW distribution substation.

Four scenarios are presented for the microgrid options that include an RNG generator. This scenario-based approach was necessary because the lifecycle GHG impact of RNG can vary considerably depending on the source of the fuel. The first two scenarios draw directly from data reported in a recent study by researchers at UC Riverside.[26] Those scenarios include RNG sourced from a dairy farm ("RNG Scenario 1") and from a landfill ("RNG Scenario 2"). The other two scenarios reflect different estimates of the lifecycle GHG emissions of landfill RNG, based on modeling performed by Enchanted Rock using Argonne National Laboratory's GREET Model.[27] In contrast to assumptions in the UC Riverside study, "RNG Scenario 3" assumes that a portion of landfill gas is vented rather than flared (i.e., burned), in a proportion consistent with what is observed in the market today. In addition to this assumption about vented gas, "RNG Scenario 4" additionally assumes a more realistic RNG transport distance of 400 miles, rather than the 3,600 mile default GREET model assumption.

For an RNG generator microgrid to provide net environmental benefits, as shown in three of the four scenarios described above, a few plausible conditions must be met. First, there must be sufficient supply of RNG (of the form specified in that scenario) that can be purchased and injected

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25 CO_2e expresses the global warming contribution of all GHGs in terms of the equivalent global warming contribution of a ton of CO_2.

26 Arun S.K. Raju, Barry R. Wallerstein, and Alexander Vu, "Optimal Pathways to Achieve Climate Goals – Inclusion of a Renewable Gas Standard," September 24, 2018.

27 The GREET Model is used to estimate the emissions output of various fuels. https://greet.es.anl.gov/

into the gas pipeline system. There are a finite number of dairy farms and landfills in the U.S., and the size of the total potential RNG resource is only a fraction of that of natural gas. Further, demand for this limited supply of RNG is expected to increase due to decarbonization efforts. However, as discussed previously, the microgrids examined in this analysis have a small fuel requirement and therefore would not be expected to outstrip RNG supply under current conditions.

Second, the RNG used to supply the microgrid must be "additive" in the sense that the RNG would not otherwise be developed for other purposes. In other words, RNG consumption must be higher with the microgrid than in a baseline scenario in which the microgrid was not developed. Practically speaking, this means that the resilience microgrid must enter into a firm contract for properly certified RNG delivered to a gas system pipeline, or purchase some form of credits that have the same effect.

Third, there must be a way to deliver the RNG to the gas pipeline system.[28] In a strict sense, the microgrid could be located at or near the site of the RNG source, with a dedicated pipeline delivering the RNG to the generator. However, the overlap between sites with RNG and locations requiring resiliency improvements likely is very limited. Less stringent delivery arrangements are also possible and can be implemented in ways that do not affect the global CO_2e calculations in this paper. For example, contractual arrangements can be made to deliver the RNG virtually over a shared pipeline. The previously referenced PG&E RFO for microgrid resilience options indicated that RNG would be injected into the gas distribution pipeline in a quantity equal to the natural gas consumed by the microgrids providing resilience to the utility's customers.

V. Conclusions

If net cost is the primary criterion for evaluating the resilience microgrid options examined in this paper, the natural gas microgrid provides the most economic value for the required level of resilience. This natural gas system can nearly break even on the basis of its earned market revenues. Gas systems also have a low up-front investment requirement relative to options that include solar-plus-storage. On a net cost basis, natural gas systems are less than 20% the cost of the cleaner RNG or RNG-hybrid systems.

If land is expensive or otherwise limited in availability, both natural gas and RNG microgrid options are attractive due to their minimal physical footprint. Figure 5 summarizes the land requirement for each feasible microgrid option analyzed in this study.

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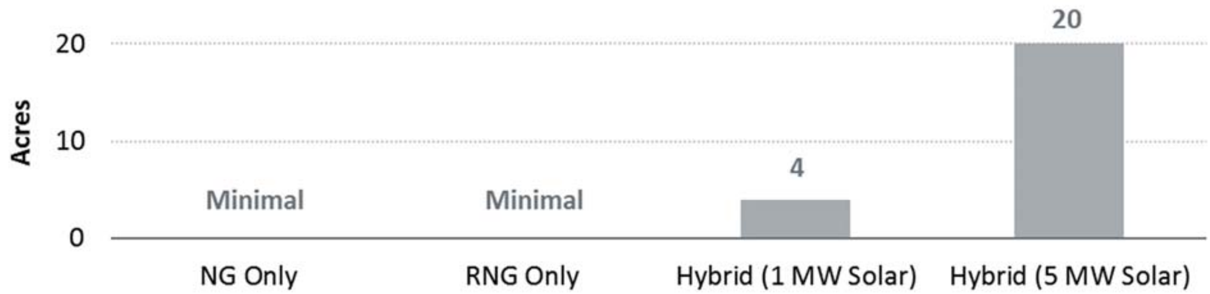
28 As is commonly assumed in greenhouse gas accounting for electricity, because total pipeline system demand for natural gas is unchanged by the addition of a resilience generator purchasing and injecting RNG, the principle of mass balance requires that an equal amount of natural gas must be displaced on the system. Thus, as with electricity, it is not necessary for the physical molecules of RNG purchased to be combusted by the resilience generator itself.

Figure 5: Microgrid Land Requirement by Configuration



Note: Results shown are for a 10 MW distribution substation.

From an environmental standpoint, all of the feasible microgrid options analyzed would have small to no adverse impact on system GHG emissions due to their infrequent use and/or carbon-free fuel source. This finding is further supported by the observation that the type of resilience microgrids we examine are likely to be deployed to very specific locations and in limited quantities relative to the overall size of the utility system.

Relative to the other feasible microgrid options, the hybrid systems provide the most significant GHG reductions, combining lifecycle GHG benefits of RNG capture with the ability of solar-plus-storage to displace output from fossil generators on the bulk electricity system. As a standalone solution, RNG can also provide GHG benefits, while natural gas systems would result in a marginal increase in GHG emissions relative a scenario where no new resilience options were deployed. In all cases, the microgrid options analyzed in this study would provide a considerable improvement over diesel generators with respect to local air quality when running. These air quality benefits, combined with the significant economic benefits identified in this study, indicate the emergence of attractive, viable alternatives to traditional diesel generation for resiliency.

Next Steps

This study presented an initial assessment of the feasibility, economics, and GHG impacts of a variety of alternatives to diesel generator microgrids. The findings provide utilities, regulators, communities, and other industry stakeholders with information on the comparative advantages of the microgrid technologies that are most commonly considered in resilience initiatives.

The MiRiAD modeling framework used in this study could be extended to additional applications. Opportunities for further research include:

- Assess the sensitivity of the market revenue estimates under market conditions from a range of jurisdictions outside of California.
- Consider resilience definitions that include a broader range of resilience requirements (i.e., both more and less stringent than the definition used in this study).

- Include an assessment of the customer value of improved reliability in the economic evaluation of the microgrid options. "Value of lost load" (VOLL) studies provide a basis for determining what value customers place on avoiding interruptions, the inclusion of which could provide a more nuanced perspective on the relative benefits of each microgrid option.

- Include additional microgrid options in the analysis such as emerging options like behind-the-meter solar-plus-storage, or conventional options like backup diesel generators.

Conclusion

In an age of pandemics and a highly digitized and electricity-dependent society, the resilience of the electric power system will continue to be an issue of utmost importance. This study demonstrates that small-scale modular generation technologies and fuel sources have evolved to the point where highly affordable, clean, and fully reliable alternatives to conventional diesel generation now exist. This development comes as the industry seeks to decarbonize and provide greater levels of resilience in the face of a variety of increasing threats.

Technical Appendix

Microgrid Cost Assumptions

Gas Microgrid

- Capital cost: $874/kW. Provided by Enchanted Rock, with inflation to $2021.
  - Reflects 7% cost savings from efficiencies due to co-locating with solar and storage.
- Fuel cost
  - Natural gas commodity: $4/MMBtu. Approximate average value based on forecasted natural gas prices in California over the next decade.
  - RNG commodity: $30/MMBtu. Derived from range of cost estimates in Jaffe et al. (2016).[29]
  - Delivery: $8.36/MMBtu. Provided by Enchanted Rock. Adjusted for inflation.
- FOM cost: $17.87/kW-yr. Provided by Enchanted Rock. Adjusted for inflation.
- Other variable cost: $15.84/MWh. Provided by Enchanted Rock. Adjusted for inflation.

Storage

- Storage capital cost: $265/kWh for a 4-hour battery. Based on NREL 2019 Annual Technology Baseline (ATB) for online date of 2021. Includes Fixed O&M of $29/kW-yr. reflecting augmentation costs. Further adjustments are applied to 2-hr and 8-hr batteries to account for fixed system costs that do not scale proportionally per kWh of storage capacity. The cost estimate above reflects the following adjustments to the NREL source estimate:
  - 10% increase to represent reduced economies of scale associated with distribution microgrid-sized projects.
  - 7% cost savings from efficiencies due to co-locating with solar/gas-fired generator.
  - 22% ITC cost savings due to co-location with solar.
    - Derated 2-12% to account for grid-charging ahead of reliability events
  - Capital cost is the present value in $2021 of a storage unit purchased in 2021 plus complete replacement after 15 years based on forecasted cost decline rate from NREL ATB.
- Variable costs:
  - Cost of purchasing energy from the market ahead of reliability events (assumes average annual energy price)

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[29] Jaffe et al., "The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute," prepared for the California Air Resources Board and California Environmental Protection Agency, June 2016. https://steps.ucdavis.edu/wp-content/uploads/2017/05/2016-UCD-ITS-RR-16-20.pdf

Solar

- Solar capital cost: $1,011/kW. Derived from NREL 2019 ATB for online date of 2021. The cost estimate above reflects the following adjustments to the NREL source estimate:
  - Increased cost by $141/kW to reflect higher assumed land cost in California ($40,000/acre at an assumed land requirement of 4 acres per MW of solar PV capacity).[30]
  - 29% increase to represent reduced economies of scale associated with distribution microgrid-sized projects over utility-scale solar.
  - 7% cost savings from efficiencies due to co-locating solar with storage.
  - 22% ITC cost savings.
- FOM cost: $14/kW-yr.
- Variable costs: None

Other cost considerations

- Interconnection costs: Interconnection costs are excluded from the analysis for all microgrids

Microgrid Operational Characteristics

Gas Microgrid

- Heat rate: 12 MMBtu/MWh

Storage

- Round-trip efficiency: 85%
- Maintains state of charge between 5% and 95%

Solar

- Single-axis tracking
- 8,760 hourly output profile from NREL System Advisor Model for Ukiah, CA location
- Annual capacity factor of 22%

Prototypical Substation Load Profile

- 8,760 hourly load shape based on 2018 hourly system load data for Modesto Irrigation District, procured via S&P Global Market Intelligence.
- Load shape scaled linearly such that the annual peak load is 10 MW (indicative of PG&E PSPS substation load levels)

30 This is increase is incremental to NREL's assumed land cost of approximately $32/kW.

Market Revenues

Resource adequacy

- RA Price: $4.72/kW-month
    - From 2018 CPUC report[31] for CAISO system contracts in NP-26
- Gas microgrid
    - 100% capacity credit
- Solar PV
    - Capacity credit equal to ELCC of 14%, based on average monthly net qualifying capacity reported by the CPUC
- Storage
    - 2 hr. storage gets 50% capacity credit
    - 4+ hr. storage gets 100% capacity credit
- Hybrid solar + storage is assigned the greater of the capacity credit of the individual solar and storage resources (capacity credit is not additive across resources)[32]

Energy revenue

- All resources are dispatched against hourly 2028 Northern CA market price projections, which were developed through nodal model simulations (converted to $2021).
- Storage and gas revenue projection also accounts for value associated with ability to respond to sub-hourly real-time price variation with limited foresight. To estimate the incremental value of DA+RT market participation over DA-only participation, we dispatch the resources against 2018 prices at the PG&E Stockton aggregated price point. The historical incremental value from redispatch is added fully to the revenues against projected DA prices for 5 years, and then derated by 50% for the remaining lifetime of the assets to account for anticipated DA vs. RT price convergence as more storage is added to the CAISO system.
- In all solar+storage cases, we assume the battery cannot charge from the grid except to ensure being fully charged entering a reliability event
- Energy revenues are derated to account for system unavailability during potential reliability events throughout the year. We assume that there are three actual events (one

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31 CPUC, "2018 Resource Adequacy Report. CPUC." August, 2019. Posted at: https://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/Utilities_and_Industries/Energy/Energy_Programs/Electric_Power_Procurement_and_Generation/Procurement_and_RA/RA/2018%20RA%20Report%20rev.pdf

32 A Proposed Decision was issued by the CPUC on May 25, after the analysis for this study was completed, defining a different approach for assigning RA value to ITC-qualifying hybrid systems. If adopted, that approach may result in lower RA value being assigned to the solar-plus-storage portion of the hybrid systems modeled in this study. The authors' expectation is that the impact of the proposed decision on this study's results would be modest, falling within the range of other sources of uncertainty related to RA compensation.

lasting 96 hours and two lasting 48 hours) and that the microgrid is additionally held in reserve for "false alarms" equal to twice this amount.

- The cost of supplying energy (either via storage charging from the grid or gas-fired generation) during three actual reliability events is netted out of market revenues

Financial Assumptions

- All resources are assumed to earn market revenues over a 30-year lifetime. Batteries are assumed to require full replacement after year 15, while solar and gas facilities are assumed to last the full 30 years.
- All prices in $2021, assuming 2%/yr. inflation
- We assume a nominal discount rate of 8.0% (real discount rate of 5.9%).

Resilience Requirements

- To provide 100% resilience, the microgrid must be able to serve all substation load for a 96-hour period at any point in the year
- We simulated 365 four-day reliability events (i.e., one event starting each day of the year). This inherently accounts for a wide range of combinations of hourly load and hourly solar output, as well as any seasonal correlation between the two, since the analysis is based on 8,760 hourly profiles for both substation load and solar PV output. The microgrid must be capable of serving all load for each of these 365 events
- Solar-plus-storage sizing assumes that the battery can charge from solar PV during the reliability event. Any remaining excess solar output (i.e., in excess of load) is curtailed and not counted toward the reliability requirement
- The battery is assumed to enter the reliability event fully charged, which assumes that the operator receives least as much advance notice of the event as the duration of the battery (i.e., a 4-hour battery would require at least 4 hours of notification)
- We analyzed a broad range of possible solar-plus-storage configurations (with solar-to-storage capacity ratios ranging from 0.25 to 4.0, and battery durations of 2-, 4-, and 8-hours). The solar+storage configurations presented in the final report are the configurations that generally have the smallest physical footprint among those projects with the most attractive economics.
- In hybrid cases, the size of the solar+storage facility is defined based on assumed technical feasibility, and then the gas generator is sized to provide 100% reliability according to the definition above.

Emissions

- CO_2e intensities consistent with CARB accounting[33]
  - Natural gas value of 84.3 kg/MMBtu reflects lifecycle emissions

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[33] As reported in Table 3 of Raju, Wallerstein, and Vu, "Optimal Pathways to Achieve Climate Goals – Inclusion of a Renewable Gas Standard," September 24, 2018.

- RNG depends on the source. We present four cases, each with the following carbon intensities:
  - RNG Scenario 1: -288.2 kg/MMBtu, based on the estimate for anaerobic digestion at a dairy farm from Raju, Wallerstein, and Vu (2018).
  - RNG Scenario 2: 36.8 kg/MMBtu, based on the estimate for landfill gas from Raju, Wallerstein, and Vu (2018).
  - RNG Scenario 3: -13.0 kg/MMBtu, based on Enchanted Rock modeling using Argonne Lab's GREET model. Estimates from Raju, Wallerstein, and Vu (2018) were replicated as closely as possible, and then the assumed amount of landfill gas that was flared versus vented was adjusted downward to an 85% vs 15% split (respectively). Less flared gas means that the carbon emissions of landfills are higher, thus assigning greater GHG reduction value to RNG that avoids the direct release of that landfill gas into the atmosphere.
  - RNG Scenario 4: -31.7 kg/MMBtu, based on the same assumptions as RNG Scenario 3, with an additional Enchanted Rock modeling adjustment of reducing the RNG transport distance from 3,600 miles to 400 miles. 400 miles is a more reasonable estimate of the distance that locally sourced RNG would travel.

- Hourly implied market heat rate is used to calculate emissions displaced by microgrid energy sold into the market (assumes renewables or natural gas-fired generation are always on the margin in CAISO)
- The analysis also includes emissions impacts associated with charging from the grid or burning natural gas/RNG during reliability events

For reference, Table 1 below summarizes the direct emissions rates of a natural gas generator relative to that of a diesel generator. Information for the natural gas generator is primarily based on test data for an Enchanted Rock system, while information for the diesel generator is based on EPA emissions standards for Tier 2 and Tier 4 generators.

Table 1: Generator Emissions Factor Comparison

	Enchanted Rock Natural Gas Generator (lb/MWe-hr)	Source	Tier 2 Diesel (lb/MWe-hr)	Tier 4 Diesel (lb/MWe-hr)	Source
VOC	0.001	NRTL Test Data [1,2]	14.11	0.42	NSPS IIII [5]
NOx	0.004	NRTL Test Data [1,3]		1.48	NSPS IIII [5]
CO	1.09	NRTL Test Data [1,3]	7.72	7.72	NSPS IIII [5]
PM/PM10/PM2.5	0.003	NRTL Test Data [1,4]	0.44	0.07	NSPS IIII [5]
SO_2	0.007	AP-42 Table 3.2-3	0.016	0.016	AP-42 Table 3.4-1
CO_2	1,395	NRTL Test Data [1]	1,555	1,555	AP-42 Table 3.4-1

Notes: Provided by Enchanted Rock. For Tier 2 diesel, VOC and NOx emissions limit applies to sum of both emissions sources.

Sources:

[1] Enchanted Rock ISO 8178 D1 weighted test cycle emissions results from a single engine at a Nationally Recognized Testing Laboratory (NRTL). Actual field test results may vary due to site conditions, installation, fuel specifications, test procedures and engine to engine variability.

[2] VOC emissions found to be below the minimum detection level of the equipment.

[3] NOX and CO emissions data are the near-zero hour non-deteriorated emission rates which are not guaranteed emissions for the purposes of air permitting. These rates are typical for lower run hours which will increase with catalyst age.

[4] PM emissions not expected to change with catalyst age, although differences in fuel quality could impact actual emissions.

[5] NSPS IIII emission limit for electric generator rated between 560 kW and 900 kW.

AP-42: Compilation of Air Emissions Factors (EPA) https://www3.epa.gov/ttn/chief/ap42/ch03/index.html

NSPS IIII: New Source Performance Standards, Subpart IIII: https://www.ecfr.gov/cgi-bin/text-idx?rgn=div6&node=40%3A7.0.1.1.1.98