The Opportunity for Propane in Microgrids

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Introduction

Microgrids and distributed energy resources play a critical role in enabling renewable energy market penetration, reducing electricity transmission and distribution (T&D) losses (which average 5% in U.S.[1]), providing resilience and partial or total independence from the electrical grid. Typically, microgrids are composed of kilowatt (kW)/ Megawatt (MW)-scale solar-PV system, kilowatt-hour (kWh)/ Megawatt-hour (MWh-scale battery energy storage (4-6 hours discharge capacity) and a backup generator system or a backup fuel cell system; operating with hydrogen, natural gas, propane, diesel, gasoline or other suitable fuels. The backup generator provides an immediately dispatchable firm resource needed for microgrids as the capacity factor for solar and wind is roughly only 30% and Lithium-Ion (Li-ion) battery storage systems are uneconomical beyond 4-6 hours of discharge capacity. Backup generators have a critical role and are powered today with conventional fuels but will be steadily displaced by drop-in replacement renewable fuels in the future. These act as the firm resources until long duration energy storage systems, such as flow batteries for example, become economical and commonplace in the future. Firm and dispatchable resources are needed to balance microgrids and avert blackout situations such as those experienced in Texas, Louisiana, California, and other states. Recently, the state of New Jersey granted $4 million for studying detailed microgrid designs as part of its ongoing Town Center Distributed Energy Resources Microgrid Program. Interestingly, the board has allowed the use of fossil fuel generators in microgrids for ensuring resilience [2]. In places where a natural gas pipeline is not available, diesel is used for backup engine generators. Propane, on the other hand, is easily transported and is the best low carbon fuel choice compared to diesel. Also, since most propane engines are stoichiometric or rich burn engines, emissions control is typically achieved using a three-way catalyst, which results in very low nitrogen oxide (NOx) emissions compared to diesel engines. Propane also does not contain any aromatics (e.g., benzene) or polycyclic aromatic hydrocarbons (PAHs) and since it is a low carbon alkane, it produces less particulate matter or soot than diesel. According to recent research at Oakridge National Laboratory (ORNL), much of the soot formed from propane engines could be attributed to the lubricant oil rather than fuel itself [3].

In terms of commonly used fuels, propane, or liquefied petroleum gas (LPG) falls in a sweet spot between hydrogen, at one end of the spectrum, and gasoline and diesel, at the other end of the spectrum. This sweet-spot, or tradeoff, is characterized by the liquid energy density, carbon to hydrogen ratio (C:H) of the fuel and ease of liquefaction. Table 1 shows this tradeoff between the various fuels in terms of liquid energy density, C:H and ease of liquefaction, transportation, and storage. For each category, green represents the most desirable property, yellow is the tradeoff and red is undesirable. As can be seen, propane or LPG is the only option that offers the best tradeoff in terms of ease of liquefaction, transportation and storage, while having a reasonable energy density and low C:H.

As shown in the table, though propane is gaseous at standard conditions, it is easy to liquefy without the necessity of cryogenic infrastructure. Ammonia could be easily liquefied as well, like propane, and is carbon free but ammonia is produced by Haber-Bosch process using hydrogen, which in turn is obtained from steam methane reforming (SMR) using natural gas (In the U.S., about 95% of the hydrogen is produced by SMR[4]). In addition, ammonia has a lower energy density. From a C:H ratio standpoint, propane falls in between hydrogen (0) or Ammonia (0) and Diesel (0.55). However, as noted before, much of the hydrogen is currently being produced via SMR. This landscape may change if "green" hydrogen is produced from water electrolysis by using electricity generated purely from renewable sources. Natural gas has a lower C:H ratio as compared to propane but is a potent greenhouse gas and needs cryogenic infrastructure to liquefy. Currently, from an economic standpoint of the customer, the usage of propane makes sense in areas where there is no supply of natural gas and/or reliable supply of electricity. Hence, propane currently occupies a sweet spot for immediate reduction in carbon emissions using low-cost infrastructure for its transportation

1. https://www.eia.gov/tools/faqs/faq.php?id=105&t=3
2. https://microgridknowledge.com/new-jersey-town-center-microgrid/
3. Splitter, D., Storey, J., Boronat Colomer, V., & Dal Forno Chuahy, F. (2020). Performance of Direct Injected Propane and Gasoline in a High Stroke-to-Bore ratio SI Engine: Pathways to Diesel Efficiency Parity with Ultra Low Soot. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).
4. https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming#:~:text=Natural%20gas%20reforming%20is%20an,reforming%20in%20large%20central%20plants.

Fuel	Liquid volumetric energy density (MJ/l)	C:H	Ease of liquefaction, transportation and storage
Hydrogen	8.5	0	X
Ammonia	11.5	0	✓
Liquified natural gas[5]	22.2	0.25	X
Propane or LPG	25.3	0.375	✓
Gasoline	34.2	0.5	✓
Diesel	38.6	0.55	✓

Table 1: Properties of various conventional fuels considered for backup power generation.

and storage in a liquid state. In other words, environmental goals can be achieved by utilizing propane without any additional costs to the customer.

In this study, two cases are presented highlighting the benefits of using propane generation systems in hybrid microgrids as compared to diesel backup generators with comparisons of economics (in terms of levelized cost of electricity (LCOE)) and emissions. The beta version of the Homer QuickStart tool[6] was used for this exercise.

Some Examples of Current Solutions

Few examples of microgrid solutions employing propane are presented here. In the rural neighborhood of Silvies Valley Ranch outside of Burns, Oregon, 600 homes (2,000-6,000 sq.ft.) are being developed under three phases, which will all be powered with off-grid microgrids including solar-Photovoltaics (PV), battery energy storage (30-70 kWh) and propane generators[7]. It is estimated that the propane generator will be used for 10% of the time and will provide the necessary resiliency when the state of charge of the battery is low.

Liberty Utilities is building a 97% renewable microgrid to de-energize four miles of transmission line located in a remote location in Sierra Nevada that is prone to wildfires[8]. The microgrid will employ 20 kW of solar PV, 68 kWh of battery backup and a propane generator. It is estimated that the propane generator will only be used for 3% of the time during the year. BoxPower[9] will provide the containerized microgrid solution for this application to help prevent wildfires.

Generac industrial power generators[10] have been employed in Kahauiki Village microgrid in Honolulu, HI and Sagehen microgrid in Truckee, CA. As again, both microgrids will be composed of solar PV with battery storage and a propane generator. For the Kahauiki Village microgrid, the propane generator will be utilized (in addition to the grid) to charge the batteries when their state of charge is low and when there is not enough solar energy. In addition, the propane generator offers additional resiliency during storms when grid outages are common and reduces the demand charges when the grid is stressed. The Sagehen microgrid was constructed to address concerns of high-tension lines and their probability to induce wildfires, thus a remote microgrid was constructed to provide power to the local residents. However, due to the possibility of low solar energy and snowy weather conditions, the containerized microgrid solution included a propane stationary generator to provide a reliable source of backup power to charge the batteries, as and when needed.

Case Study 1: Light Commercial Applications (Community Housing)

A. Economics

A simple problem was formulated in Homer Quickstart with the intent of installing a microgrid in San Diego, CA (Note: San Diego was chosen for maximizing the usage of solar energy) for a community housing (light commercial) with a load of 200 kWh/day. A baseline hybrid system was created using a Generic

Parameter	Value
Installed price of diesel generator	$12,500[d]
Diesel generator operations and maintenance (O&M) cost	$0.75/hr[d]
Minimum load	25%
Diesel price	$2.42/gallon[11]
PV installed price	$3/W (AC load)[d]
Hourly variability in load	20%[d]
Daily variability in load	10%[d]
Battery price	$7168/battery (95% roundtrip efficiency)[d]
System converter price	$300/kW (95% efficient inverter and rectifier)[d]
Average diesel fuel to electric conversion efficiency	31%[12]

Table 2: Baseline system assumptions.

Case/Parameter	Propane COTS generator	Propane CHP generator	Propane SOFC
Total installed price	$9,000[13]	$62,500[14]	$60,000[15]
Replacement costs	$20,948[16]	0[17]	0[17]
System life	Same as baseline diesel (6 years)[d,18]	40,000[19]	40,000[15]
O&M without fuel	$0.75/hr[d] ($0.039/kWh)	$0.2/hr[19,20] ($0.01/kWh)	$0.48/hr[15] ($0.025/kWh)
Fuel to electricity efficiency of device	21.5%[21]	31%[22]	35%[15,23]
Propane price ($/gallon)	1.67[11]	1.67[11]	1.67[11]

Table 3: Parameters and assumptions for propane backup generation systems.

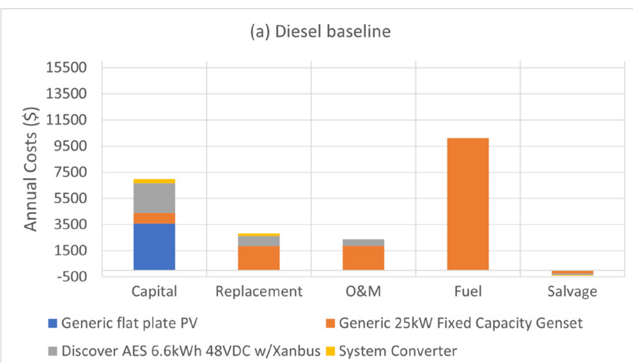
5. Compressed natural gas is an option, but the storage and fueling infrastructure of compressed natural gas is generally higher than LPG.
6. https://www.homerenergy.com/
7. https://microgridknowledge.com/off-grid-microgrids-oregon/
8. https://microgridknowledge.com/liberty-utilities-microgrid-california/
9. https://boxpower.io/
10. Honl, C., Engine-Driven Generators and their Criticality in Microgrids, White paper, 2019. Available for download at : https://microgridknowledge.com/white-paper/engine-driven-generators-microgrids/
11. Note, this is average commercial fuel price for California for the year 2018.
d Indicates default value in Homer QuickStart.
12. https://www.generac.com/Industrial/products/diesel-generators/configured/25kw-diesel-generator
13. Based on typical 25 kW COTS propane generators
14. Typical 25 kW natural gas/propane CHP generators are approaching $3/W and hence it has been assumed a CHP generator without heat integration package, associated controls and simplified installation would approach $2.5/W.
15. Manufacturing Cost Analysis of 1, 5, 10 and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications, Battelle Memorial Institute Report. Prepared for US Department of Energy, 2017.
16. The number of replacements for the baseline propane generator are assumed to be the same as baseline diesel and replacement costs are calculated akin to the baseline.
17. The CHP and fuel cell units have a runtime of >40,000 hours and will not need to be replaced.
18. https://www.generac.com/Industrial/professional-resources/news-whitepapers/power-connect-newsletter/archived-articles/september-2018/considering-natural-gas-fuel
19. https://www.axiom-energy.com/custom-remote-power
20. The cost of replacing, oil, oil filter, air filter and spark plugs was considered to be $250 per maintenance.

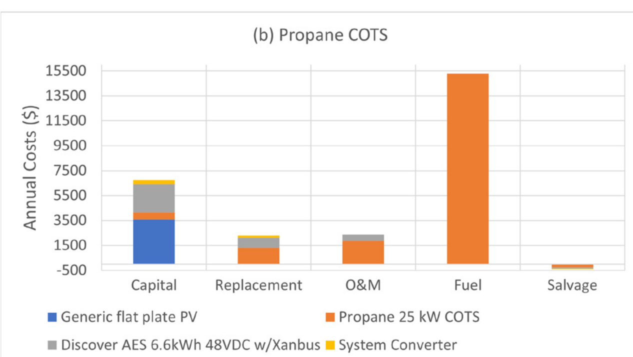
flat plate photovoltaic (PV), an energy storage system (Discover AES 6.6 kWh 48 VDC with Xanbus system control panel) and a 25-kW generic diesel backup generator. A nominal discount rate of 6% was assumed with an inflation rate of 2% for the LCOE calculations. The assumptions for the baseline system costs are outlined in Table 2.

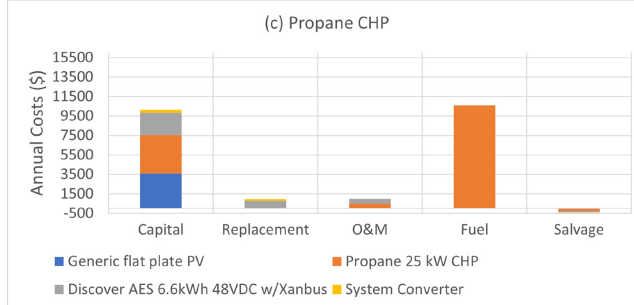
The baseline simulations provided four solutions and the solution with the least LCOE was selected here for analysis. This resulted in a hybrid solution with 19 kW of Solar PV, 31 kWh of battery storage (5 strings of the Discover AES) and a 25 kW generator. The system converter was sized at 17 kW. The Solar-PV produced nearly 40% of yearly kWh load, while the engine provided nearly 60% of the yearly kWh load. The engine was operated for nearly 2500 hours per year i.e., at a capacity factor of ~29%.

For comparison purposes, three other cases were considered of which the first case employed a commercial off-the-shelf (COTS) propane generator, the second case employed a combined heat and power (CHP) engine generator (without the heat capture unit) and third case employed a propane solid oxide fuel cell (SOFC). Table 3 shows the parameters for these cases.

Figure 1(a-d) shows the unincentivized breakdown of the annualized costs of the hybrid microgrid with the baseline diesel, propane COTS generator, propane CHP generator and propane SOFC scenarios. In all these cases, all the other components of the micro-grid (viz. PV, battery, converter, and balance of plant) were all assumed to be identical. Figure 2 shows the associated impact on the unincentivized levelized cost of electricity (LCOE) for all these four cases. Note, no net-metering has been assumed here.







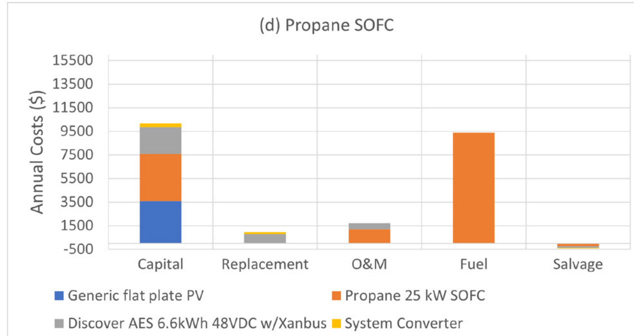


Figure 1: Unincentivized annualized costs for the hybrid microgrid with a) Diesel generator b) Propane COTS, c) Propane CHP and d) Propane SOFC generation systems.

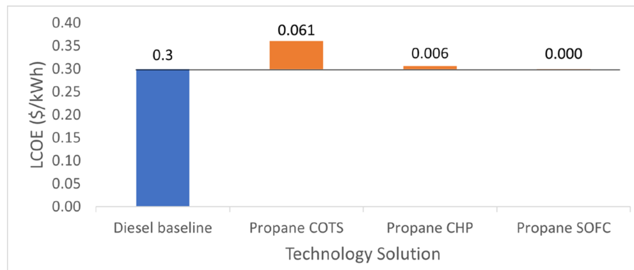


Figure 2: Unincentivized LCOE of the hybrid microgrid system with different generation systems.

As can be seen from the figures, the hybrid microgrid with the propane COTS solution leads to a worse LCOE primarily driven by the lower fuel conversion efficiency of the backup generator (21.5% efficient propane engine compared to 31% efficient diesel engine) despite propane's lower energy prices on a per gallon basis However, it must also be noted as per Table 1, propane has 66% of the energy content of diesel on a per gallon basis. If, instead, a modified version of the CHP generator is used (i.e., generator only without the heat integration package), the capital cost is significantly higher than the COTS solution, but the replacement and fuel costs are much lower than the COTS solution leading to an LCOE that is on par with the diesel baseline. The fuel cell solution provides the lowest fuel expenses but slightly higher O&M costs and is also on par with the diesel baseline and propane CHP solution. Note, the propane COTS solution is more expensive than the diesel baseline since the capacity factor of the backup generator is 29%. For scenarios, with capacity factors less than 10%, the fuel costs will be comparable yielding similar LCOEs.

21. https://www.generaccorporate/media/library/content/all-products/generators/resi-comm/protector/generac-generators-spec-sheet_protector-gaseous-25kw-60kw.pdf
22. Based on data of the Lochinvar XRGI25 using natural gas from the DOE CHP eCatalog. A propane fueled system is expected to behave similarly although combustion phasing calibration may be needed: https://chp.ecatalog.lbl.gov/home
23. 40% efficiency is easily possible for SOFCs but start time may not be acceptable. With catalytic partial oxidation reformers, 35% efficient natural gas and propane SOFCs are entering the market with start-up times <30 minutes.

B. Environmental Benefits

Emissions of NOx, carbon monoxide (CO) and carbon dioxide (CO_2) for the baseline diesel system (without emissions after-treatment system but complying with EPA New Source Performance Standard emissions for non-emergency compression ignition engine generators) are available from Homer QuickStart. Though the current study does not quantify emissions from propane COTS generator due to lack of test data, it is widely known that typical propane generators use a three-way catalyst that are effective in mitigating NOx, CO and unburned hydrocarbon (HC) emissions. These emissions are generally lower than their diesel counterpart. When the propane CHP system is used there is significant emissions reduction potential for NOx, CO, and CO_2 as these systems are currently being certified for CARB distributed generation emissions standards of 0.07 lb/MWh NOx, 0.1 lb/MWh CO and 0.02 lb/MWh volatile organic compounds (VOC)[22, 24] using a simple three-way catalyst. SOFCs that employ after-burners to burn off anode tail-gas (CO + H_2+ H_2O) also produce negligible NOx and CO emissions.

As seen from Figure 3, the tailpipe CO_2 emissions of the propane COTS systems is higher than the baseline diesel system due to its lower fuel conversion efficiency; however, if a CHP engine is used for this purpose, which has nearly the same fuel conversion efficiency as the diesel generator then the propane CHP generation system leads to ~14% reduction in CO_2 emissions due to its lower C:H. The SOFC leads to nearly a 24% reduction in CO_2 emissions since its fuel conversion efficiency is higher than the rest of the systems and propane has a lower C:H compared to diesel. Figure 4 shows the reduction in NOx and CO emissions enabled by the propane CHP generator compared to a diesel generator based on available data[22]. As can be seen from the figure, the CHP generator leads to near-zero NOx and CO emissions (0.88 kg/yr), which is a substantial improvement over the incumbent diesel generator. The fuel cell system is also expected to have similar, if not lower, NOx and CO emissions.

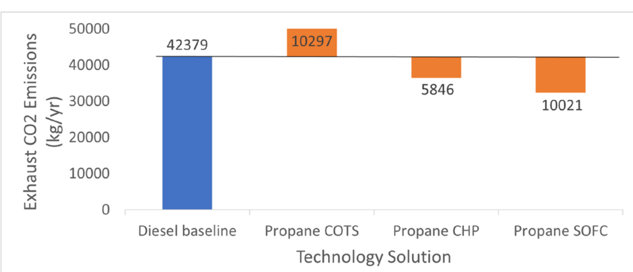


Figure 3: Tailpipe CO2 emissions of the four generation systems.

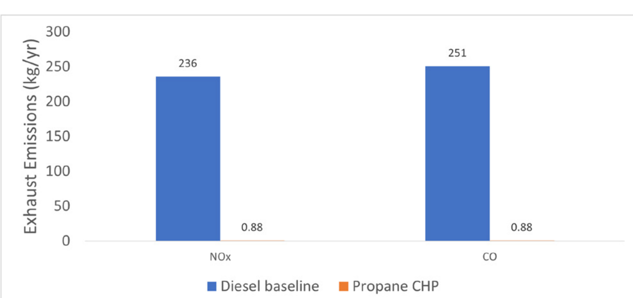


Figure 4: NOx and CO emissions for the baseline diesel and propane CHP generation systems.

Case Study 2: Large Commercial Applications

A. Economics

Another simple case was simulated in Homer QuickStart for Mammoth Lakes, CA, where propane is prevalent in several communities. A large commercial establishment was simulated with a daily load of 2500 kWh/day. A baseline hybrid system was created using a Generic flat plate photovoltaic (PV), a generic 100 kWh Li-ion energy storage system and a 400 kW diesel backup generator. Like the previous case, a nominal discount rate of 6% was assumed with an inflation rate of 2% for the LCOE calculations. The assumptions for the system costs are outlined in Table 4.

Parameter	Value
Installed price of diesel generator	$200,000[d]
Diesel generator operations and maintenance (O&M) cost	$0.0375/kWh[d]
Minimum load	25%
Diesel price	$2.42/gallon[11]
PV installed price	$2/W (AC load) -- lower than default value of $3/W
Hourly variability in load	20%[d]
Daily variability in load	10%[d]
Battery price	$400/kWh (95% roundtrip efficiency) -- lower than default value of $600/kWh
System converter price	$300/kW[d] (95% efficient inverter and rectifier)

Table 4: Baseline system assumptions.

Again, the solution with the least LCOE was selected here for analysis. This solution resulted in a hybrid solution with 588 kW PV, 1500 kWh of battery storage (15 strings of the Li-ion battery) and a 400 kW diesel generator. The system converter was sized at 305 kW. The Solar-PV produced 86% of the yearly kWh load while the engine generator provided 14% of the yearly kWh load. The engine was operated for nearly 500 hours per year i.e., at a capacity factor of ~6%.

For comparison purposes, two other cases were considered in which a Siemens propane lean-burn engine generator [25] (which is also used in CHP applications [26]) was used in the first case and a propane SOFC was employed in the second case. Table 3 shows the parameters for these cases.

Case/Parameter	Propane COTS generator	Propane SOFC
Total installed price	$200,000[d]	$466,484[27]
Replacement costs	$0[d]	$0[d]
System life	>15 years[d]	>15 years[d]
O&M without fuel	$6.4/hr ($0.02/kWh)[28]	$7.1/hr ($0.022/kWh)[27]
Fuel to electricity efficiency of device	35%[25,26]	40%[27]
Propane price ($/gallon)	$1.67[11]	$1.67[11]

Table 5: Parameters and assumptions for propane backup generation systems.

24. https://ww3.arb.ca.gov/regact/dg06/finalfro.pdf
25. https://assets.new.siemens.com/siemens/assets/public.1599737241.9bc49909-dd4d-4381-8b58-6a0736407342.gasengines-overview.pdf
26. Based on data for Martin Energy Group: MEG S450P-HW propane CHP unit from DOE CHP e-catalog.
27. Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications, Battelle Memorial Institute Report. Prepared for US Department of Energy, 2016. Scaled it based on a 250 kW SOFC system.

Figure 5(a-c) show the unincentivized breakdown of the annualized costs of the hybrid microgrid with the baseline diesel generator, propane COTS generator and propane SOFC generations systems. In all these cases, all the other components of the micro-grid (viz. PV, battery, converter, and balance of plant) were all assumed to be identical. Figure 6 shows the associated impact on the unincentivized levelized cost of electricity (LCOE) for all the above cases.

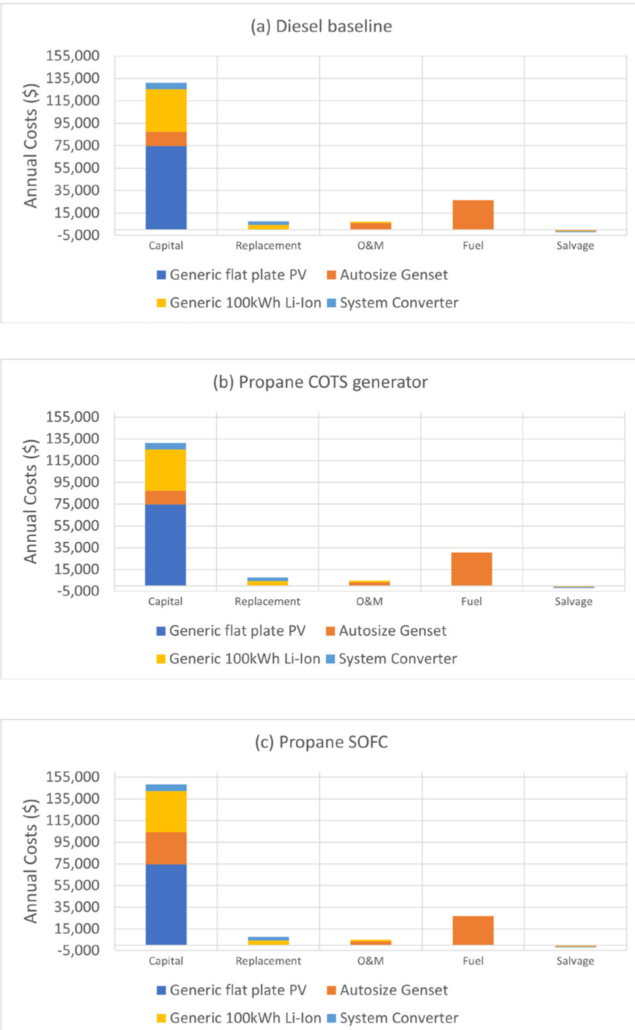


Figure 5: Unincentivized annualized costs for the hybrid microgrid with a) Diesel generator b) Propane COTS generator, and c) Propane SOFC generation systems.

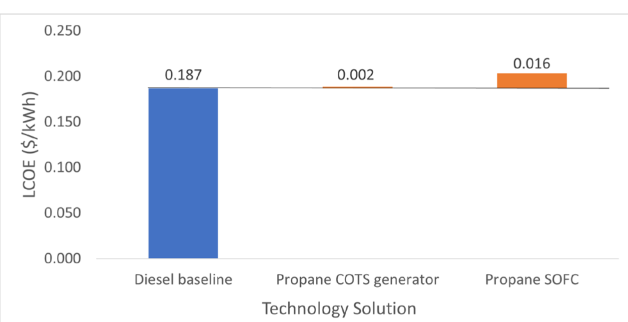


Figure 6: Unincentivized LCOE of the hybrid microgrid system with different generation systems.

28. https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Recip%20Engines.pdf

As can be seen from the figures, a hybrid microgrid with the propane COTS generation solution is competitive to the backup diesel system. The slightly higher fuel costs with propane, due to the lower propane generator efficiency (35%) compared to diesel generator (39%), is equally balanced by the lower operations and maintenance (O&M) costs of the propane generator to yield the same levelized cost of energy (LCOE) as the incumbent diesel solution. The fuel cell solution, though the most efficient (40%), leads to a higher LCOE (~9% higher than the baseline diesel solution) due to its higher capital cost.

B. Environmental Benefits

As earlier, emissions of NOx, CO, CO2, and HC for the baseline diesel system without an exhaust after-treatment system are available from Homer QuickStart. The engine-out NOx, CO and HC emissions factors of the propane COTS generator were taken from the Department of Energy CHP e-catalog for the Martin Energy Group: MEG S450P-HW system [26]. It is noted that this package is also available with lower emissions factors but with a penalty in fuel conversion efficiency[26].

Figure 7 shows the exhaust CO2 emissions for the different generation systems. As can be seen, the COTS propane generator system leads to ~4% reduction in CO2 emissions relative to the diesel generator, while the propane SOFC system can lead to ~16% reduction in CO2 emissions.

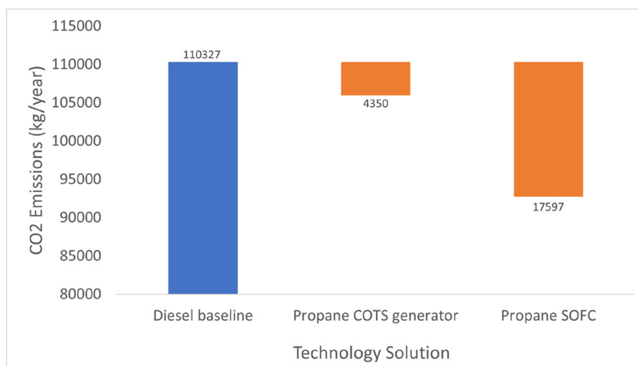


Figure 7: Tailpipe CO2 emissions for different generation systems.

Table 6 shows the engine-out NOx, CO and HC emissions for the baseline diesel generator and COTS propane generator systems, both without exhaust after-treatment systems. In terms of criteria pollutants, the propane engine-out emissions are significantly lower for NOx (~63% lower) and CO (~40% lower) but higher in HC as compared to the diesel generator (diesel generator is ~90% lower in engine-out HC emissions). Engine-out HC emissions can be effectively mitigated via the use of an oxidation catalyst, which will be required in all these engines. In addition, the incremental cost of adding exhaust after-treatment systems such as urea-selective catalytic reduction (SCR) for NOx mitigation, oxidation catalysts for CO and HC mitigation, urea consumption costs and exhaust after-treatment controls are assumed the same between the diesel and propane generation systems and hence the LCOE should be comparable. Table 6 also provides projected tailpipe-out emissions and projected tailpipe-out emissions factors for the criteria pollutants assuming a 90% SCR conversion efficiency and 95% oxidation catalyst conversion efficiency. Chiefly, for the propane engine generator, NOx, CO, and HC emissions factors of 0.15 g/kWhe, 0.13 g/kWhe and 0.09 g/kWhe, respectively are extremely encouraging. Fuel cell system-out emissions i.e., downstream of the anode tail-gas afterburner are still considered to be negligible and will lead to near-zero emissions.

	Diesel generator	Propane COTS generator
Engine-out NOx (kg/year)	641	238.7
Engine-out CO (kg/year)	682	407.3
Engine-out HC (kg/year)	30	294.4
Projected tailpipe-out NOx (kg/year)	64.1	23.9
Projected tailpipe-out HC (kg/year)	34.1	20.4
Projected tailpipe-out CO (kg/year)	1.5	14.7
Projected tailpipe-out emission-factor for NOx (g/kWhe)	0.4	0.15
Projected tailpipe-out emission-factor for NOx (g/kWhe)	0.21	0.13
Projected tailpipe-out emission-factor for NOx (g/kWhe)	0.01	0.09

Table 6: Engine-out and projected tailpipe-out emissions for diesel and propane COTS generators.

Observations and Opportunities for the Propane in Light and Large Commercial Microgrids

Light-commercial microgrid (<100 kW generation system):

Propane is competitive to diesel for microgrid applications requiring resiliency when employing the "right" generator.

There is a critical need for high fuel conversion efficiency generators that can perform at diesel-like efficiencies. The propane industry does not have to look far for this solution as current micro-CHP engines meet the need. Albeit with a higher capital cost, the lower maintenance costs and durable design of these engines with diesel like efficiencies at this size range enable an on par LCOE. However, significant reductions in carbon dioxide emissions (92 metric tons of CO2 reduction over the microgrid lifetime) with near zero emissions of NOx and CO with a three-way catalyst (3.7 metric tons of NOx and 3.7 metric tons of CO emissions reductions relative to a 25 kW diesel generator without after-treatment) can be realized with the propane solutions. Thus, propane generators in a hybrid microgrid prove out to be both cost-effective and environmentally friendly, which is a tough tradeoff to achieve.

Propane also opens the doors for fuel cells in hybridized microgrids, which are also on par in terms of the economics and can lead to near zero NOx and CO emissions with additional CO2 reductions (158 metric tons of CO2 reduction over the microgrid lifetime) compared to a diesel backup generator.

With offerings such as propane fuel cells and CHP engines, the concentrations of exhaust emissions are reduced to such an extent that the application of carbon capture technologies may become more viable from a technical standpoint (although economics may not be forgiving at this scale) due to higher concentrations of CO2 in the exhaust and near-zero criteria pollutants in the tailpipe.

Large commercial microgrid (>100 kW generation system):

Propane is competitive to diesel for microgrid applications requiring resiliency when employing commercial-off-the-shelf lean-burn engine solution.

There is a critical need for high fuel conversion efficiency stoichiometric, or rich-burn, engine generators that can perform like diesel generators. A stoichiometric exhaust gas recirculation(EGR) solution is one way to achieve high efficiency and low NOx, CO and HC tailpipe-out emissions using a closed-couple three-way catalyst. Perceptible reductions in CO2 (68 metric tons of CO2 reduction over the microgrid lifetime), NOx (0.63 metric tons of NOx reduction over the microgrid lifetime) and CO emissions (0.22 metric tons of CO reduction over the microgrid lifetime) can be achieved with current solutions. HC emissions are higher than the diesel incumbent solution, as compression ignition engines have a very high combustion efficiency than lean-burn spark-ignited engines. However, with a 95% efficient oxidation catalyst, the HC emission factor of the engine could be as low as 0.09 g/kWh.

Propane fuel cells have a higher LCOE as compared to the incumbent diesel generator but can enable near-zero emissions for NOx, HC, and CO. Tremendous CO2 reductions (277 metric tons) can be realized with fuel cells due to their higher fuel conversion efficiencies; however, the design needs to be done carefully to achieve a tradeoff between system efficiency and start-stop capability.

Carbon capture may still be economically challenging at this scale but achieving ultra-low emissions of criteria pollutants will require high catalyst conversion efficiencies for lean-burn engines or stoichiometric engines with high fuel conversion efficiencies and a three-way catalyst for mitigating emissions.

For further efficiency improvements, the waste heat from the generator can be captured and stored using thermal energy storage systems (e.g., molten salt), and utilized for district heating or process heating to supplement the community housing's or commercial facility's heating needs.

Both propane engines and fuel cell systems can also open the doors for the usage of renewable propane (obtained currently as a byproduct of renewable diesel or sustainable aviation fuel using feedstocks such as used cooking oil/grease/animal fat etc.) as a drop-in replacement for conventional propane. Blends with conventional propane and renewable propane can also be possible solutions in the future for further mitigating CO2 emissions.