INTERCONNECTION AND SIZING OF COMBINED HEAT & POWER IN RENEWABLE ENERGY MICROGRIDS

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SUMMARY

The addition of combined heat and power (CHP) systems within renewable energy microgrids creates substantial opportunities and benefits as well as several significant challenges. CHP systems provide a resilient source of dispatchable generation, future potential for sustainability benefits when operating on hydrogen or renewable natural gas, and often sizable utility cost savings.

This paper explores technical and operational challenges related to including CHP in microgrids based on real-world microgrid experience. Some of these topics include how to interconnect and operate different assets that may or may not qualify for net-metering, and how to size solar photovoltaic (PV) and battery energy storage systems (BESS) with CHP in renewable energy microgrids. In summary, this paper will describe how best to use CHP within behind-the-meter microgrids.

INTRODUCTION

To encourage increased renewable penetration and adoption, most states throughout the United States have regulations and tariff structures for net-metering of renewable energy sources. "Net-metering" refers to the ability to export electricity from renewable energy production to the grid during periods of overproduction. This exported power is credited on the customer's utility bill against periods where utility power is imported. If the export and import of power from the utility are roughly balanced over a 12-month period, the customer can maximize the benefit of the on-site renewable energy production.

If the electricity could only be used on-site (no export or net-metering), the result would be either smaller system sizes or the need for installing BESS to store and discharge excess power. While the cost of BESS has decreased significantly, this still could mean increased cost and reduced utility savings for the customer.

One of the unique challenges for designing behind-the-meter CHP systems is that typically the interconnecting utilities will not allow CHP systems to export power. Even though some CHP systems do export power to the grid, that export power is only credited at the real-time or day-ahead electricity rate during that period. On average throughout the year, the real-time and day-ahead electricity rates tend to be lower than the electricity rates offered to commercial/industrial customers. Net-metered renewable energy sources offset electricity charged at the higher commercial/industrial tariff rates for power imported from the utility.

It may be beneficial during periods of high real-time electricity rates to export. However, in most cases it is economically advantageous to size a CHP system assuming no utility export. This is referred to as "electrical load-following" operation.

LOAD-FOLLOWING OF BEHIND-THE-METER CHP SYSTEMS

Most behind-the-meter CHP systems are designed for electrical load-following and are not intended to export power to the grid. Not only will utilities limit export of power, but many utilities will also require a minimum utility import at all times. The most common prime movers for CHP systems are reciprocating engines and gas turbines. These prime movers cannot ramp up or down as quickly as other distributed energy resources, such as batteries. The minimum utility import is put in place to protect against power export if site loads fluctuate more than the ability for the CHP systems to respond. For renewable energy microgrids, the CHP may also need to respond to fluctuations in solar/wind energy production because of quickly changing weather conditions (cloud cover, change in wind speed, etc.). Additional equipment can also be installed, such as batteries or load banks, to help mitigate this further.

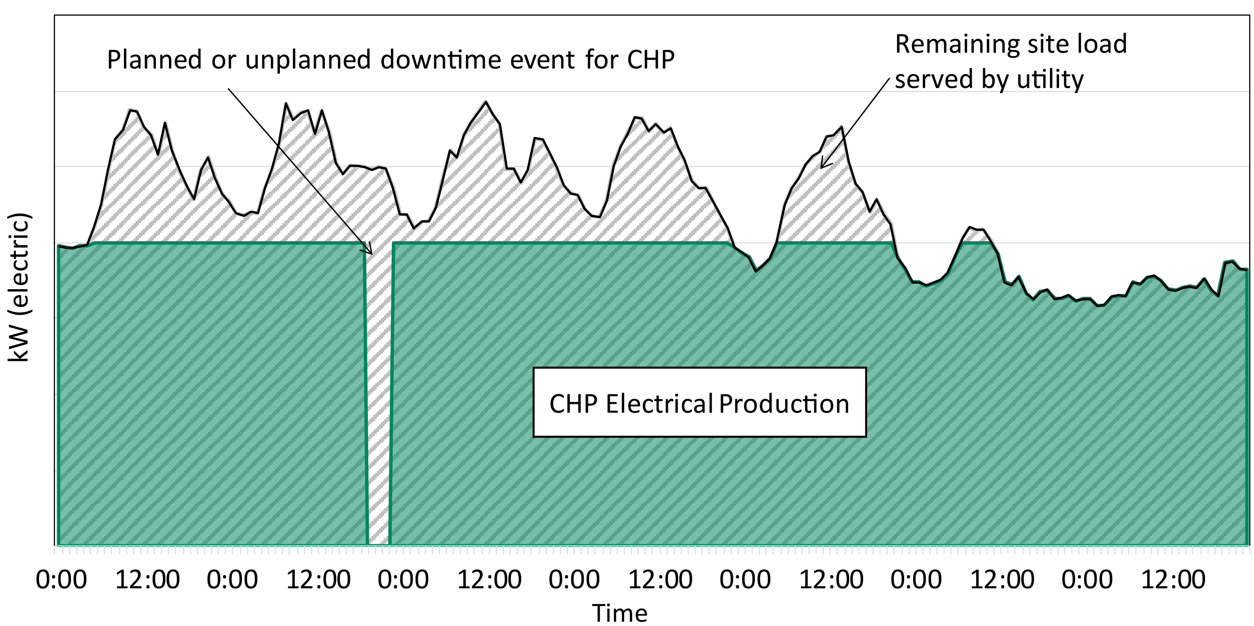
Other operating modes for CHP systems include "peak shaving" (reducing utility demand peaks) and "thermal load-following" (economic dispatch based on the value of the thermal energy production). While these other operating modes are sometimes applied, the most common operating mode for behind-the-meter CHP systems remains "electrical load-following." This electrical load-following operation is governed by certain conditions and constraints, ranging from equipment specifications to requirements from the interconnecting utility:

- Minimum import requirement from utility: This variable parameter is set on a site-by-site basis based on utility requirements, facility load types, etc.
- Load-following capability: CHP systems will load-follow between max output (100%) and minimum desired output (typically 50% of nameplate).
- Other vendor constraints on partial load operation: CHP equipment vendors limit partial load operation with constraints, including time to restart following a shutdown, minimum operating time after a restart, and the ratio of operating hours to CHP restarts[1].

A sample representation of electrical load-following with no minimum utility import is shown in **Figure 1**. The CHP operates close to full load (baseload) throughout the week, with some limited partial load operation on the weekend period. A sample representation of electrical load-following with a minimum utility import of 5% to 10% of the rated nameplate capacity is shown in **Figure 2**.

The CHP still operates close to full load most of the week. However, additional partial load

FIGURE 1. CHP operation—no minimum utility import.



[1] 2G Energy Technical Manual. "Partial load and start-stop operation" (TA-008 December 2021 pages 6-12)

operation must occur when site loads, net of the minimum utility import, fall below the rated capacity of the CHP. The trade-off between larger CHP systems versus higher operating hours will be discussed later in this paper. In general, the CHP system economics will be optimal when the number of hours the prime mover can be operated is maximized.

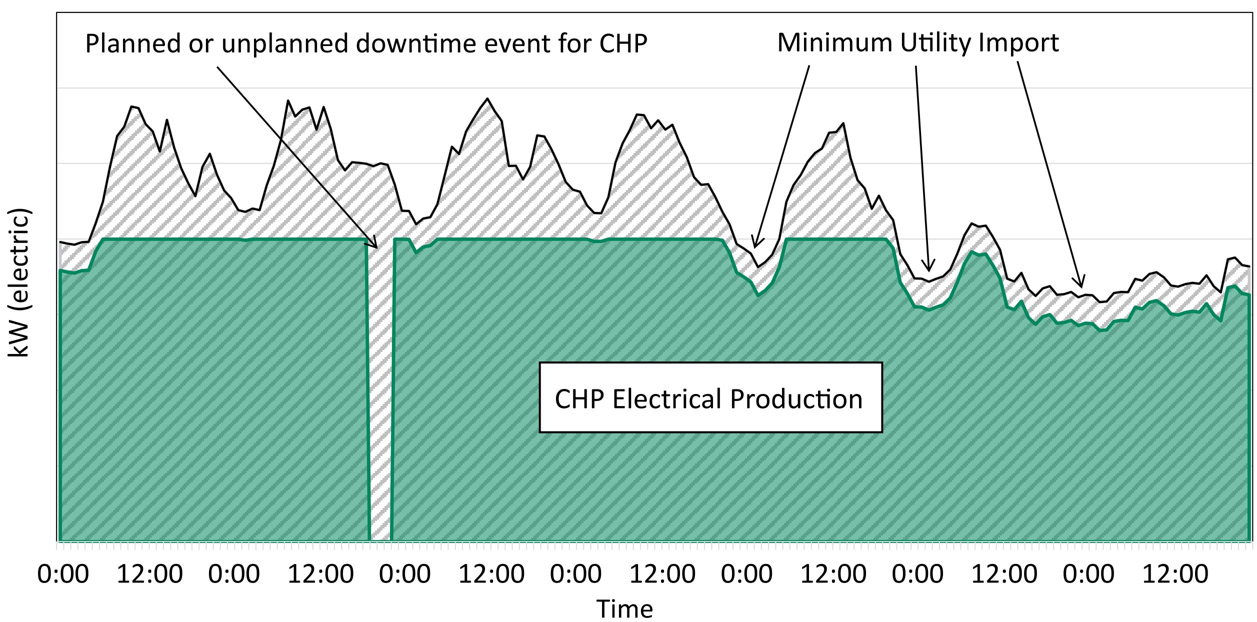
USE CASES – PV + CHP – MODELING AND INTERCONNECTION

For almost all behind-the-meter CHP systems, export of power to the grid is either not allowed or it is not financially justified. The solar PV systems are the opposite and can take advantage of net-metering and export excess power to the grid. What is the best approach for power export and interconnection when you have both PV and CHP as part of a renewable energy microgrid?

Ultimately, the interconnecting utility will determine whether the microgrid project qualifies for net-metering, what protection devices are needed, and whether a minimum utility import is required.

There are several different methods for modeling and interconnection of PV + CHP microgrids, but the following methods are two

FIGURE 2. CHP operation with minimum utility import.



that have been used for designing microgrids now in commercial operation.

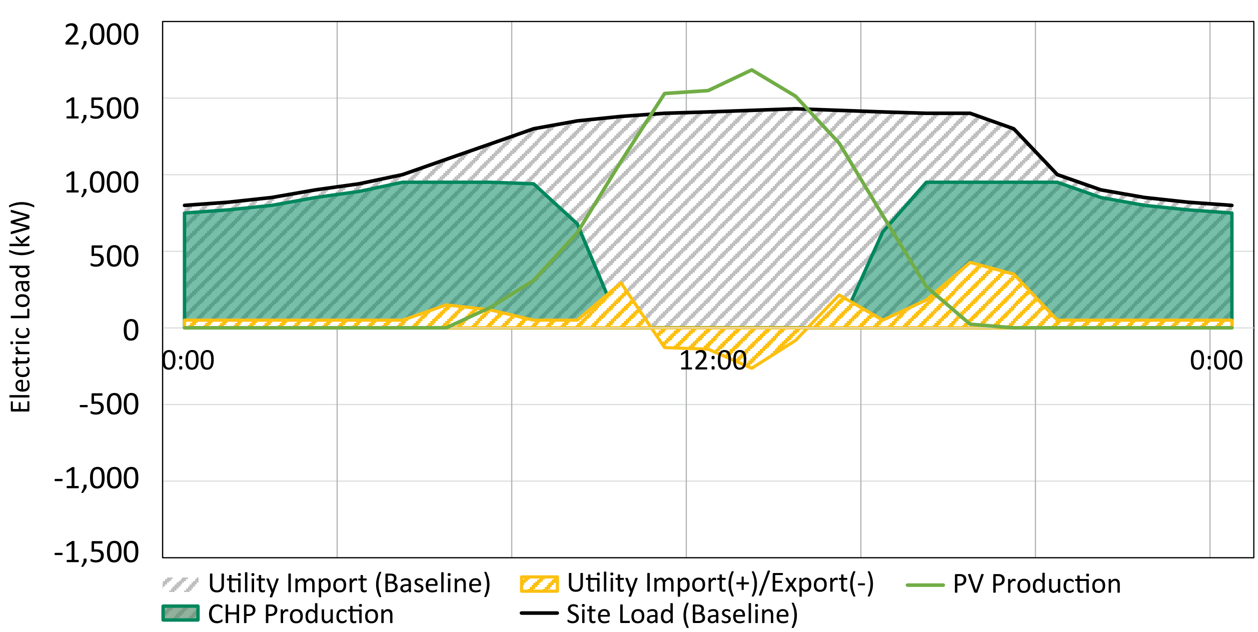
- Method #1: For the purposes of the CHP, total PV + CHP production can never exceed site load. Therefore, the CHP electrical production must be ramped down as PV production increases. CHP power output will equal zero whenever power from the PV is being exported to the grid because PV production is larger than the site load. This is the most conservative approach in terms of CHP electrical production.
- Method #2: CHP electrical production can never exceed site load (ignoring any PV production). CHP power output can be greater than zero when power is being exported to the grid because any net power being exported to the grid is net-metered PV power. This will result in increased run-time for the CHP and better economics.

Method #1 involves comparing the combined electrical production of the PV and CHP subsystems against the site load to determine how the CHP should be dispatched. The CHP will effectively electrical load-follow the net site load (site load net of PV production). Because many utilities may not allow any CHP power to be exported, the CHP will always be shut down when power is exported by the PV array.

Figure 3 shows an example of Method #1. The export occurs when the green line for PV production is above the black line (site load). The CHP in this example is 1000 kW with a 50-kW minimum utility import requirement. The PV array has a nominal capacity of 2000 kWac.

As the sun comes out in the morning and the PV production starts to ramp up, the CHP power must ramp down to avoid exporting any power. The CHP will be fully turned off when the net site load is below the minimum turndown level of the prime mover (50% load or 500 kW). During this intermediate period, power is being imported from the utility (shown in yellow) because the CHP is turned off and the PV production has not yet exceeded the full site load. Eventually, the PV production will increase above the site load and power will be exported.

FIGURE 3. Method #1: Modeling and dispatch of PV + CHP microgrids.



The PV system will get to take advantage of net-metering, and the CHP will operate during periods of high site loads or low PV production (at night or on cloudy days). If operating hours for the CHP prime mover drop too low because of the interaction with the PV array, the CHP can be designed smaller or be removed altogether.

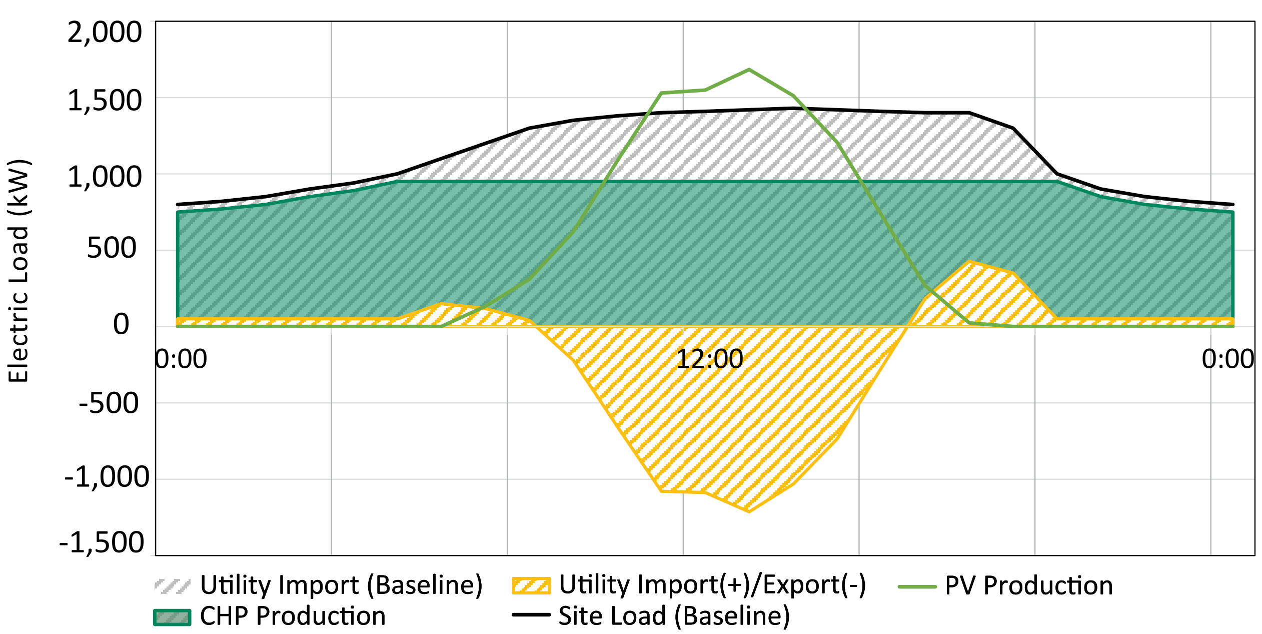
Method #2 seeks to maximize the benefit of having net-metering for PV systems. In **Figure 4**, the CHP operation is no longer constrained by the production of electricity from the PV array. The CHP will be dispatched to electrical load-follow the site load, similar to standalone CHP systems that have no solar PV installed. The CHP operates at partial load at night but remains operational and stays at full load for the majority of the day.

As the sun comes out in the morning and the PV starts to ramp up, the CHP does not have to change its operation. When the combined production of the CHP and PV exceed the site load, any additional power will be exported. More power is exported to the grid because of the increased CHP production.

In Method #1, the CHP must be sized to account for both the characteristics of the site load profile and the interaction with PV array production. In Method #2, the CHP is only sized to account for the characteristics of the site load profile. The balance between CHP size and PV size will vary project to project based on economic factors (utility rates, available incentives) and qualitative factors (sustainability, resilience). If the CHP or PV is significantly larger than the other asset in the microgrid, both methods for load-following will have similar results.

Electrical load-following assumes the electrical production is the most valuable source of revenue for the CHP, so both methods seek to maximize electrical production. Thermal load-

FIGURE 4. Method #2: Modeling and dispatch of PV + CHP microgrids.



following will be more advantageous when the thermal energy produced by the CHP system is very valuable. An example is a site served by a centralized district-heating or district-cooling system. These district systems tend to have high heating and cooling costs, creating an incentive to maximize the CHP thermal energy production and offset these existing costs.

For a CHP system with thermal load-following, the PV production could need to be curtailed to keep the CHP prime mover above minimum electrical load. When the CHP and PV assets in a microgrid are electrical load-following, the system is designed to avoid curtailment and maximize the use of the net-metered renewable energy generation. The power of the sun is free, so the goal of net-metering is to maximize the PV production that happens when the sun is shining.

Ultimately, the utility will decide the equipment required to complete an interconnection for the PV + CHP microgrid. Both methods are technically feasible with the use of controls and relays. It is critical to understand the requirements of the local utility to ensure the project is modeled and sized correctly.

USE CASES – CHP + BESS – INDOOR AGRICULTURE EXAMPLE

As previously discussed, the economics of CHP systems generally are maximized when the number of hours the prime mover will operate is maximized. For projects with a positive "spark spread"[1], each additional run hour generates incremental savings. Maintenance costs per run hour also go down because the fixed costs of maintaining the prime mover can be spread out over more run hours.

Is the optimal solution always to size a CHP system to the "base load" to maximize operating hours (8000+ hours/year)? Not necessarily. Larger CHP systems take advantage of economies of scale, resulting in a lower upfront $/kW capital cost when compared to smaller systems. The best overall economics may be with a larger CHP system sized to the "peak load," taking advantage of the lower $/kW cost, additional energy production, and relatively high operating hours (6000+ hours/year with more partial load operation).

For facilities with lower occupancy at night or on the weekends, it is risky to size the CHP system close to the "peak load" without first considering the economic impact of lower operating hours. Examples of such facilities include office buildings, manufacturing facilities with shift work, and indoor agricultural facilities with advanced growth schedules. Renewable energy technologies, such as PV and BESS, or

[2] U.S. Energy Information Administration. "An introduction to spark spreads" (Today in Energy. February 8, 2013).

fast-response generation resources, such as natural gas generators, can complement CHP systems for facilities with a lot of variation in the load profile shape.

An example of a project where load profile shape came into play for CHP and microgrid sizing was from an indoor agriculture facility in the northeastern U.S. **Figure 5** shows the hourly load profile for the facility. During a typical week, electric load at the facility drops significantly for 3 hours, 1-2 times per day. This is done deliberately as part of their growth process. The grow lights are turned off and the facility is quickly cooled down.

Indoor agriculture is an ideal application for CHP. These facilities are energy-intensive and use a lot of electricity for the grow lights. They also must be temperature-controlled, resulting in high seasonal heating and/or cooling loads.

Some facilities also inject supplemental CO_2 into the facility to help with the growth process. The exhaust from the prime mover of a CHP system produces additional CO_2 that can be captured and used in the facility, creating savings from offsetting expensive supplemental CO_2 tanks. For this specific facility, the big challenge is once or twice per day the load drops to a fraction of peak load. How should the CHP system be sized to maximize economics?

This type of load profile presents several options. Option #1 is to size a CHP for the minimum "base load" (500 kW), ensuring the prime mover operates the maximum number of run hours at or close to full load. Option #2 is a larger rated capacity (1000 kW), ensuring the prime mover operates close to the maximum number of run hours but with increased partial load operation (down to 50% or 500 kW minimum operating load). Option #3 is sizing the prime mover closer to "peak load," at 2000 kW or 3000 kW, providing more power but having to shut down during the periods of low electric load.

FIGURE 5. Indoor agriculture facility—hourly load profile.

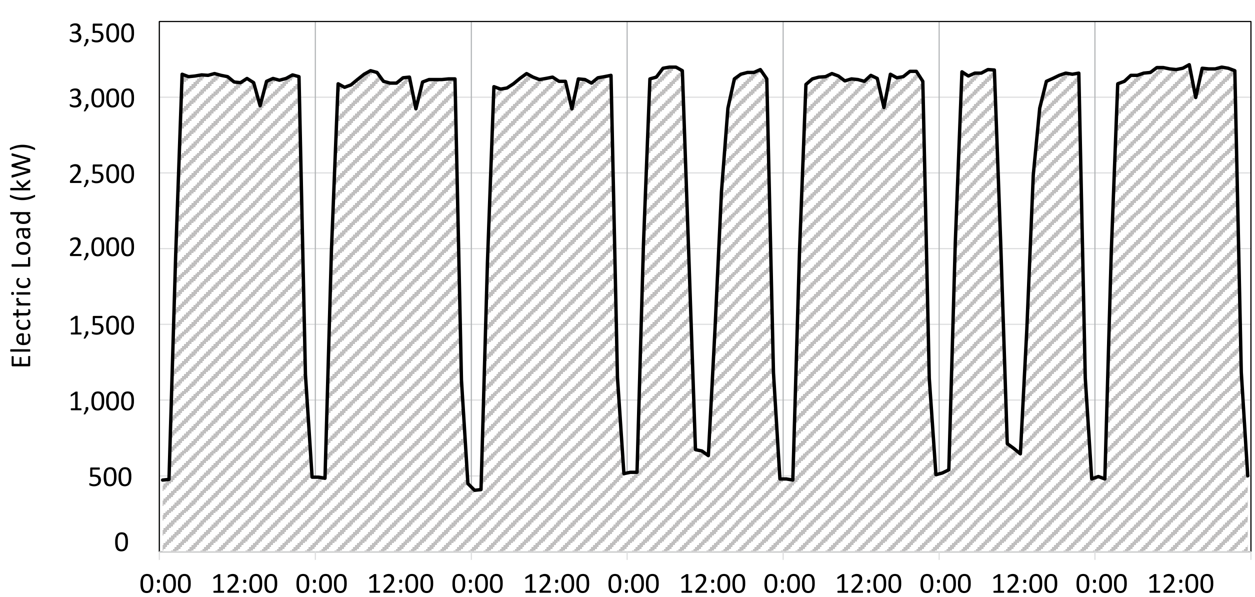


Table 1 highlights the differences between each of these three options. Option #3 has the highest electrical production, despite producing close to zero kWh during the 1000 hours per year where the greenhouse shutdowns occur. The installed cost of each option is estimated using equipment quotes from CHP vendors and installation estimates from engineering contractors. Option #3 has the lowest per kW installed cost and the lowest installed cost per kWh of electrical production, assuming 20 years of CHP operation similar to the Year 1 production estimates.

This is a simplified financial comparison to highlight the sensitivity of reduced operating hours and economies of scale. Even with 3-hour shutdowns 1-2 times per day, Option #3—with a larger 2000 kW CHP—is best. This result was confirmed with a full financial model incorporating 15-minute load profiles, maintenance cost estimates, utility rates, and available incentives. The 2000-kW CHP operates approximately 7000 hours per year and had the best financials because of economies of scale and higher savings from additional electricity, hot water, chilled water, and CO_2 production. The larger CHP option also provides more dispatchable generation for resilience needs.

TABLE 1. Comparison of CHP Sizing Options for Northeast U.S. Agricultural Facility

	Option #1 500 kW	**Option #2 1000 kW**	**Option #3 2000 kW**
Peak period kWh (˜7000 hours/year)	3,500,000 kWh	7,000,000 kWh	14,000,000 kWh
Shutdown period kWh (~1000 hours/year)	500,000 kWh	500,000 kWh	0 kWh
Total kWh (Year 1 production)	**4,000,000 kWh**	**7,500,000 kWh**	**14,000,000 kWh**
Total operating hours (Year 1)	8000 hours	8000 hours	7000 hours
Estimated installed cost (equipment + installation)	**$2,000,000**	**$3,000,000**	**$5,400,000**
Estimated installed cost ($/kW)	$4000/kW	$3,500/kW	$2,700/kW
Installed cost per kWh (years 1-20 of kWh production)	**$0.025/kWh**	**$0.020/kWh**	**$0.019/kWh**

Figure 6 shows the amount of electrical production and utility import from a 2000-kW CHP. The CHP prime mover cannot operate when electrical load is below 1000 kW.

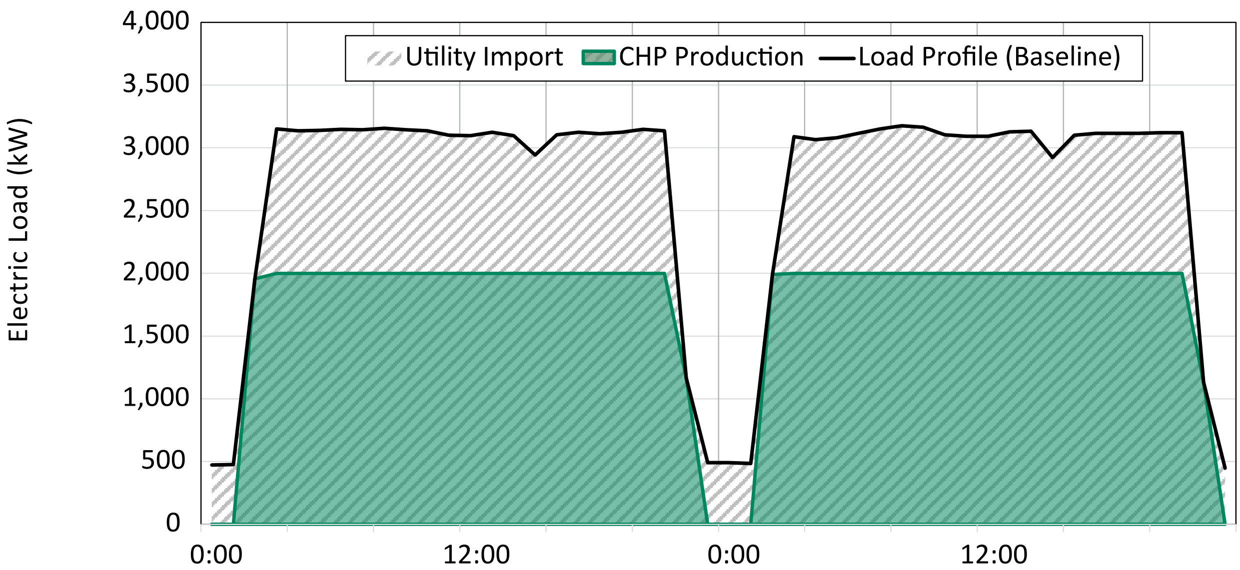
Because the project originated as a microgrid opportunity, we also evaluated PV and BESS. Many indoor agriculture facilities have large glass roofs to let light in and louvered glass panels to let air in or out of the grow facility. An example of the roof for a modern greenhouse is shown in **Figure 7**.

There was some available space on the site for a ground-mount PV array, but a large rooftop PV array was not feasible because the roof could not be disturbed. The proposed small ground-mount PV array did not have a significant impact on the shape of the facility load profile, so it is not considered here in the analysis.

Battery energy storage is one of the most flexible distributed energy resources, and the use cases are endless. The most common behind-the-meter use cases are renewables smoothing, energy arbitrage, and peak shaving. The use-case of adding BESS with CHP is particularly attractive for our indoor agriculture

FIGURE 6. Aerial view of the roof for a large modern greenhouse.

FIGURE 7. Electric production for a 2000-kW CHP electric load-following dispatch.



example because of the load profile shape. The BESS would be dispatched as follows:

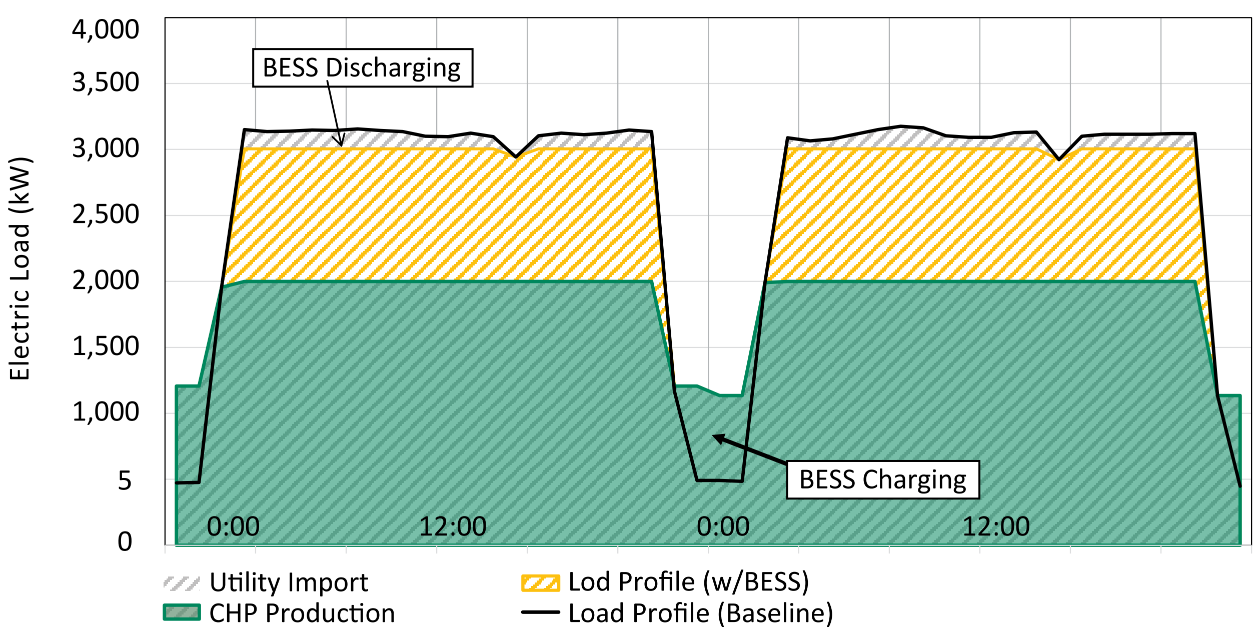
- The BESS would be fully discharged in advance of any shutdown occurring at the facility, and the CHP would continue operating during the shutdown to charge the battery.
- During the day, when facility electricity use is high, the BESS can be dispatched for energy arbitrage or peak shaving.
- Because the facility chooses when these low electrical load events occur, the discharging and charging of the BESS can be done with complete foresight.

With a 1000-kW/3000 kWh (3-hour) BESS, it was determined the operating hours could be increased to 8000+ hours per year. **Figure 8** shows an example of the operation of the CHP with the BESS.

The CHP production and operating hours increase because the CHP will serve the facility's electrical needs and charge the battery. When the BESS is charged, it can be discharged during the day for peak shaving. Because the load profile is relatively flat over a 20-hour period, the amount of peak shaving will be a limited to a maximum of 150 kW for a 3000-kWh BESS. The achievable electrical demand peak savings is likely lower because it cannot be fully predicted what the load profile shape will look like every day during the month.

In addition to increased operating hours and higher financial savings, the reduction in the number of start-ups and shutdowns of the CHP prime mover will reduce maintenance and improve reliability. The project did not proceed past this initial feasibility stage, but the initial analysis suggested the BESS improved the financials of the project if we could capture additional revenue from state incentives and demand response programs.

FIGURE 8. Electric production for a 2000-kW CHP with 1000-kW/3000 kWh BESS.



Battery energy storage is one of the most flexible distributed energy resources and will likely become a mainstay in all renewable energy microgrids as costs come down and the benefits are more fully valued by utilities and power network participants.

CONCLUSIONS

Variable renewable energy resources (PV) and dispatchable resources (CHP) can complement each other as part of a renewable energy microgrid. Flexible resources (BESS) have countless use cases, and the sizing and mix of resources can be chosen for a specific application. The mix of renewable and dispatchable resources will also depend on the success criteria for a project (economics, sustainability, resilience).

A balanced microgrid solution will have favorable economics, while providing significant sustainability and resilience characteristics. Additional microgrid configurations can be chosen to maximize resilience or sustainability, most likely with additional cost. The financial performance of a CHP system will depend on the thermal load that is available to offset, electricity production, overall CHP efficiency, operating hours/start-ups, utility rates, and equipment/maintenance costs. A reduction in the number of start-ups and shutdowns of the CHP prime mover will reduce maintenance and improve reliability.

The dispatchable nature of CHP prime movers provides a significant resilience benefit, and renewable natural gas and hydrogen fuels provide the promise of future sustainability benefits, too. It is critical to install a properly sized CHP system within a renewable energy microgrid to maximize the benefits and future opportunities.

2000-T142
March 13, 2023