Performance and analysis of retail store-centered microgrids with solar photovoltaic parking lot, cogeneration, and battery-based hybrid systems

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Abstract
To examine the potential of distributed microgrids using sustainable energy sources centered on retail store parking lots, this study provides a methodology to simulate medium-scale solar photovoltaic (PV) + combined heat and power (CHP) + battery hybrid microgrid systems deployed at big box retail stores. First, a method is provided to agglomerate 15-min load data for a community of residences in the region of the store to provide baseline electricity load profiles. The systems are then modeled using dispatch strategies previously shown to be stable for smaller, but more dynamic loaded systems. The methodology is demonstrated with a case study for a Walmart Supercenter located in Nova Scotia, Canada. The electricity generated by each component of the hybrid system is coupled and optimized to fulfill the electric demands of the local community. The results provide the total electricity generated by the PV + CHP + battery hybrid system, total operating hours by each unit, fuel consumed, and hourly energy produced by each unit. The results show that such microgrid systems could serve the electrical needs of ~1000 people (350 residences) for each parking lot of 3.5 MW PV system and CHP unit of 1 MW. The technical viability of this approach warrants future work.

KEYWORDS
battery, cogeneration, combined heat and power, microgrid, photovoltaic

1 | INTRODUCTION

There is large interest in distributed generation with renewable energy devices1-5 as improvements in the technologies have made conversion of our electrical system away from fossil fuels both possible6,7 and preferable in the context of global climate destabilization.8-11 Solar photovoltaic (PV) technology, in particular, is promising because of widespread availability12,13 and properties of clean, secure, reliable, and affordable electricity. For example, solar installation cost in the United States have declined by 15% in the past 8 years and is expecting reduction of around 40% in next 4–5 years.14 Additionally, PV technology helps mitigate risks of electric rate inflation.15-20 Research and development in PV is often
focused on utility scale systems because of economy-of-scale, and the ability to maintain conventional grid infrastructural and management. There has also been significant research into small-scale PV deployment at single family residences. This is technoeconomically challenging because in addition to lack of scale for pricing there are many impediments to individual PV systems including: (1) lack of access to financing, (2) suboptimal orientation or tree shading, (3) high soft costs, and (4) power issues such as load matching for off grid systems or power quality issues for grid-tied systems.

A potential solution for bridging the gap between large and small PV systems is the integration of PV into microgrids. There have been several demonstrations of this and theoretical work into such systems showing promising economic potential. A microgrid consists of discrete energy systems which includes distributed energy sources like PV with energy storage units (e.g., batteries), and load/demand management. In microgrids the load can operate as an island (standalone), parallel to the grid. Microgrids have been designed to integrate several renewable energy resources like solar, wind, geothermal, and combined heat and power (CHP) systems. During low solar-PV flux times, a CHP system turns on to maintain loads and these systems have been modeled with dispatch strategies sufficient to cover even the most dynamic loads such as small communities, single buildings, and even a single-family residence. Those with PV as the primary energy generation source have lower greenhouse gas (GHG) emissions than conventional centralized grid systems. In addition, microgrids can increase efficiency of fuel use via CHP, which further reduces emissions. Finally, microgrids can also improve power quality, reducing stress on transmission and distribution systems, and providing reliability and security to end users.

Despite these technical benefits, microgrid deployment has been very limited in the USA, with only 216 microgrids rated a total of 1948 MW renewable energy capacity to date (2015). For example, it has been used on some campuses and as the Department of Defense Title 10 USC 2911 requiring military operations to obtain 25% of energy generation from renewable energy resources by 2025, a fraction of U.S. military bases have adopted systems to maintain functionality in the event of grid power loss. Clearly there are additional applications for technically-sound economically viable microgrid deployment modes.

One such opportunity is parking lots. North American urban planning now includes large “big-box” retail stores with expansive parking lot areas. Big-box retailers such as Walmart, Kohl’s, Costco, Staples, Target and IKEA are already covering their rooftops with PV and are familiar with the techno-economic optimization process of meeting their own electrical demands. However, the parking lots of such retailers present an additional opportunity as medium-scale solar farms, far exceeding in store demands. Thus, retail stores could provide an anchor for an aggressive distribution of microgrids in North America.

To examine this potential, two distinct types of analysis are needed (1) determination of the ability to meet electric loads of surrounding residences for such a PV + CHP + battery hybrid microgrid system using generic parking lot areas and (2) a more granular technical and economic analysis based on the specific electrical and thermal loads of an individual big box store. This study provides a novel methodology to provide answers to the first type of analysis by simulating a medium-scale PV + CHP + battery hybrid microgrid systems deployed at big box retail stores. This study is the first of its kind to attempt to probe the potential of PV-covered parking lots as a hub for community access to green electricity. Specifically, 15-min load data were identified for a community of residences in the region of a store with a large parking lot to provide baseline electricity load profiles. Next, a new method is provided to agglomerate the data to larger time steps and uses “week-shifting” to address peak demand issues with a scaled profile. The systems are then modeled with the Hybrid Optimization Model for Electric Renewable (HOMER) Pro Microgrid Analysis tool using dispatch strategies investigated at the household level, the methodology is demonstrated with a case study for a Walmart located in Nova Scotia, Canada. The results are presented and discussed to determine the initial technical viability of retail-store centered microgrids.

2 METHODOLOGY

The framework for this study revolves around developing a theoretical three-part system (PV, CHP, and battery) that can be deployed at a Walmart Supercenter to provide electricity for the local community. A case is presented where these three system sizes were the variable and sized for the application. These three systems interact to provide the electric load for a community in Nova Scotia, Canada. Three types of modeling were used to determine the performance of the system: PVSyst was used to model the available solar flux, the load profiles were generated from smart meter data provided
by Nova Scotia Power Inc. and HOMER Pro Microgrid Analysis Tool was used on these two datasets and new dispatch strategy to model the entire system.

### 2.1 Generic retail microgrid design strategy

A diagram of the hybrid system containing a PV, CHP, and battery component is shown in Figure 1. This system has only AC electric loads and a thermal heating load. The solar array and cogen unit both generate electricity. In order to meet the electric demand, conversion (rectifiers, inverters) and battery storage are incorporated. For the electric load, an inverter is installed to convert DC outputs from the battery sub-system and the solar PV array, into an AC output, which is compatible with the load. Similarly, a rectifier is included in the design to store excess AC output from the CHP sub-system in the battery sub-system. Parallel topology is used for the system electrical components.\(^{18,29}\) The PV and the battery unit will first be used to fulfill the load demand. Any electrical demand not able to be met with solar energy will be delivered using the CHP unit (CCHP).

The output of the solar PV array is fed to the DC-DC buck converter with in-built maximum power point tracking in order to step down the DC voltage. The DC output is then converted into AC with the use of an inverter which is provided to the load. The CCHP consists of a micro-turbine (MT) and electrical generator, which converts natural gas into both electricity and heat. The excess electricity generated by the PV unit and the CCHP is stored into the battery. This analysis does not include the thermal portion of the load, which is covered by the CHP and a main boiler.

### 2.2 Dispatch strategy of hybrid system

The dispatch strategy is planned in order to control the overall combined hybrid system such that the electric load requirements of the community are met. The priority is first given to the PV technology then battery and then the CCHP in order to fulfill the load demand and to increase the overall fuel efficiency of the system. When the PV output is equal to the electric load from the selected number of community household’s aggregate load then it will try to fulfill the electrical load demand. It the electricity generated by the PV canopy is greater than the community load, it will match it and then store the remaining electricity in the battery system. The energy stored in the battery will be used only during times when there is insufficient direct PV generation to meet the community electrical demands. If the load is greater than the PV first, the combination of the PV and battery will attempt to meet the load. If battery and PV is not able to meet the demand then the battery will be deactivated and the CHP will be used to meet the demand. If PV and CHP generated electricity is equal to the load then it will fulfill the electrical demand and control is now provided to fulfill the thermal demand of the store. If the electricity generated by the PV and CHP is greater than the electrical load of the community, then it will fulfill this demand and the excess will be stored in the battery if it is not fully charged. Once the battery is charged and the thermal demand is fulfilled the CHP is deactivated for a time (the store is presumed to have a primary heating system and the CHP is only used to supplement it). If the combination of the PV and CHP
does not fulfill the electrical demand, then the battery is added so that all three are used to meet the demand. Once the community's electrical demand is fulfilled, the CCHP is deactivated. The simulation uses this dispatch strategy in order to minimize GHG emissions while matching the load. Full details and logic for this dispatch strategy are covered in Reference 52.

2.3 | Simulation and case study

Walmart Stores, Inc., a very popular American multinational retail corporation, consists of 11,532 retail stores under 72 banners in 28 individual countries, with annual revenue of US$485.7 billion. In the USA alone, Walmart has over 5200 retail stores with 3400 of them being “Supercenters”. These Supercenters, occupy an average footprint of 18,300 m² (197,000 ft²). The parking lot is typically 1.5 times the size of the building or greater. Walmart has already committed to improve sustainability and has installed 105 MW of rooftop PV. Moreover, Walmart aspires to be powered 50% by renewable energy by 2025, while currently 29% of its operations is powered with renewable energy.

The solar irradiation data on an hourly basis needed for input in the simulation for Nova Scotia region was obtained from PVSyst 6.3.9. Depending upon the packing factor, area of parking lot and solar flux data, a preliminary sizing of PV was done. Load demand data, excessive energy generated by PV was used to size the battery and the CHP. With the block diagram and dispatch strategy the model was simulated using HOMER Pro Microgrid Analysis Tool (3.1.3) to generate the electricity needed for a set number of average residences, which amounted to 350 residences surrounding a Walmart Supercenter in Nova Scotia. There are currently 13 Walmart Supercenters in Nova Scotia that fit this model. The modeled system, with sizing/performance calculations given below, is comprised of a parking lot sized PV system, CHP, battery bank and converter. The hourly load requirements for residences in Nova Scotia, representing the surrounding community, were obtained from the Nova Scotia electricity utility and detailed below.

2.3.1 | Electric load data

Whole-house electricity load measurements at 15-min time-steps were obtained from smart meter data provided by Nova Scotia Power Inc. (NSPI) for 160 houses located throughout Nova Scotia. The sample consisted of both electrically heated and non-electrically heated homes. This study focuses on houses that do not use electricity for heating needs (space and/or water) so that the method and results are generally applicable across the northern U.S. and Canada. A total of 26 houses in the dataset met this criterion. Because data from these houses was available for up to 3 years, separate years of data for each house were considered to be unique house profiles. There are 25 profiles from 2012, 21 profiles from 2013, and 15 profiles from 2014, totaling 61 unique profiles.

In order to provide sufficient data an entire community, 350 unique houses were required. Thus, an appropriate technique was necessary to “derive” more profiles from those that were measured in 15-min intervals. Simply scaling these profiles by a factor of 350/61 was found to create unrealistic electricity demand peaks and valleys. Downscaling the time-step from 15-min to 60-min (an aggregation method) does not properly address these unrealistic peaks and valleys by aggregation, as shown in Figure 2.

To reduce this aggregation effect, week-shifting is considered a reasonable candidate for profile creation because outdoor temperature is not a large influence on the electricity consumption of lights, appliances, and plug loads. A total of six new sets of profiles were created by week-shifting the original profiles forward or backwards by 1, 2, or 3 weeks, thus avoiding significant seasonal fluctuations, while maintaining both the day-of-the-week and the time. The effect of week-shifting versus scaling is shown in Figure 3. On the left-hand side, a ‘scaled’ profile is plotted for 1 day and on the right-hand side the sum of all of the original and week-shifted profiles is plotted. The resulting ‘peak’ magnitude is decreased by about 17% by week-shifting versus scaling and unrealistic peak and valley loads on the microgrid community thus avoided. The resulting 350 week-shifted profiles are applied throughout the rest of this study.
2.3.2 | PV sizing

The PV are to be located on awnings over the parking lot of the retail store. The packing factor and area of the Walmart parking lot at Nova Scotia was determined to provide the PV system size. Packing factor is the ratio of size of solar panel installed to the area of the space where solar panels are installed. An example packing factor value of 170 W/m² for a supermarket in Germany was used. The PV size was calculated by multiplying the packing factor by the area of Walmart parking lot at Nova Scotia, Canada.
The PV size is calculated by Equation (1)\(^\text{32}\):

\[ P_{sw} = PF \times Aw \]  

(1)

where, \( P_{sw} = \) PV module size at Walmart Supercenter Nova Scotia, kW; \( Aw = \) parking lot area of Walmart Supercenter, m\(^2\); \( PF = \) packing factor, W/m\(^2\).

From Walmart parking lot area (\(Aw\)) which is 21,000 m\(^2\)\(^\text{67}\) and packing factor (PF) which is 170 W/m\(^2\) the PV size (\(P_{sw}\)) calculated is 3.57 MW. The PV system size is thus constrained by the parking lot area.

### 2.3.3 Battery sizing

The limited PV power constrained by the parking lot area is then used to constrain the battery bank size. Specifically, the excess energy generated by the PV is used to determine the size of the battery. This excess energy can be stored in the battery and can be used to supply energy when solar energy is unavailable. The hourly electric load demand and the electrical energy generated by the solar sub-systems during a peak solar flux summer day (also on an hourly basis) is used for sizing and is shown in Figure 4. According to the hourly energy generated by the PV module is determined as the product of solar flux, efficiency of the solar module and the total module area (SAM-2015 1.30) for all the 350 houses and is observed in Equation (2)\(^\text{57}\):

\[ E_{pv} = S_F \times \eta \times A \]  

(2)

where, \( E_{pv} = \) PV energy generated in kWh; \( S_F = \) solar flux in W/m\(^2\); \( \eta = \) conversion efficiency of PV module in percent (%); \( A = \) PV module area in m\(^2\).

The excess energy generated by the solar PV sub-systems is the difference between the energy generated each hour by the PV and load demand for the hour for all the 350 houses and summing up positive values, which can be calculated using Equation (3).

Overall the excess electrical energy generated by the solar PV system is:

\[ PV_{ex}(\text{kWh}) = E_{pv} - E_L \]  

(3)

where, \( E_L = \) load demand, kWh.

To store this excessive electric energy, the battery size was determined with Equation (4)\(^\text{78}\). The battery used for this purpose is large format lithium-ion with depth of discharge of 50% to promote long life. It has a nominal voltage of 700V\(_{DC}\), as per systems supplied by various manufacturers on the market today\(^\text{79,80}\).

![Figure 4](image-url)  

**Figure 4** Nova Scotia: Electrical energy generated by PV each hour and load demand each hour of 350 houses on July 1st. The input parameters were \( \eta = 17.3\% \) and \( A = 33.6 \text{ m}^2 \).
where, $E_L = \text{daily load demand, kWh}; A_d = \text{autonomy days}; D = \text{the depth of the discharge of the battery in percent (\%)}; V = \text{the voltage (nominal) of the battery in V}.$

Load demand during the peak summer day (July) for all 350 houses is around 5194 kWh. The excessive energy generated is around 14,099 kWh which is obtained using Equation (3). The battery size and autonomy hours calculated using Equation (4) is 17,313 Ah and 32 h respectively. Typical containers of large format lithium ion batteries and converters hold 1 MWh per Twenty-Foot Equivalent. Therefore, approximately 14 units would be required to account for inefficiency and capacity degradation with cycling.

### 2.3.4 CHP sizing

The CCHP comes in discrete units (65 kW, 200 kW, 1000 kW). The CCHP chosen is Capstone Turbine Corporation, GEM Energy having size of 1000 kW to meet the demand when the PV is unable to provide power and its performance rating has been provided in Reference 81.

Natural gas is burned. The combustion products are then used to turn the turbine blades and spin the electrical generator. Net power output of this CCHP is 1000 kW and the total heat recovered from heat recovery unit is around 1301 kW. The CHP size is chosen so that it can match the load demand which can be obtained by subtracting PV energy from load demand of all 350 houses. So, the CHP size selected is 1000 kW. The heat recovery was assumed to go towards meeting the thermal demand for the Walmart. Any thermal load demand not met with the CHP would be provided by a conventional heating system and during times where the CHP system provides more thermal energy than demand it is dumped.

### 3 RESULTS AND DISCUSSION

To explore the results of the system shown in Figure 1 with a battery size of 14 MWh, PV size of 3.57 MW and CHP size 1 MWe was used as the input for the simulation and the average hourly electrical energy produced per month by all the three units are shown for region of Nova Scotia, Canada. From the simulation results hourly power generated by the PV, CHP, and the battery state of charge during the whole year is shown in Figures 5, 6 and 7 respectively.

A summary of the system configuration performance in Nova Scotia is shown in Table 1. The results explore the nominal sizes for solar PV, battery, and CHP against the average hourly electrical energy produced per month by the three energy sub-systems were charted in Figure 8. In order to meet the demand, all three electrical sub-systems are operated. The average hourly electrical energy produced for 350 houses by solar, cogen and battery are found to be 64.1, 48.23, 166.15 kWh respectively for the month of December. When aggregating the electrical energy produced by all three sub-systems (PV, CHP, and battery) it can be observed in Figure 8 that it matches with the average hourly load demand, which is 269.42 kWh for December. This indicates that if a greater solar fraction is to be obtained from an area constrained by the size of the parking lot, energy efficiency and load shifting would be needed in the community. On the other hand,
in June the load demand is relatively low. Thus, it can be fulfilled primarily using solar energy with the PV and battery units as can be seen in Figure 8. This has the result of significantly reducing the operating time for the cogeneration sub-system. As can be seen by the results the method used was successful and the solar PV, battery storage and the CCHP were all sized correctly. This is the case as they were able to meet the electrical load demand for all 350 houses around Walmart at Nova Scotia.

As can be clearly seen by the results this study showed that hybrid PV + CHP + battery systems scaled around parking lots can clearly provide the electric load in a microgrid system by deploying PV on big box store parking lots. These microgrids can be of significant scale to matter to the local communities. The average family size in Canada is three,82 meaning that each retail parking lot-centered PV-powered microgrid can serve the needs of more than 1000 people. Thus, the results indicate such PV-powered microgrid deployments could benefit big box retailers and residences around them.
Such systems could benefit the parking lot owner in several ways. First, having an PV awning over parking lots will protect customers and employees that park under them from inclement weather (e.g., rain, hail, sleet and snow), which is particularly relevant in the case study region. Second, the same canopies will reduce the heat inside customer vehicles from the greenhouse effect during the summer. By increasing the comfort of their customers by providing shading in summer and precipitation avoidance year round, it can be expected that retail parking lot owners would improve their store selection when compared to retail establishments with no covered parking. Third, parking lot owners would provide a clear mode of green consumerism which may also increase store selection and thus sales. Combined and particularly because green electricity from the parking lot would be viewed as a community asset, such systems would be expected to garner local community good will. Future work is needed to quantify all of these effects.

It should be pointed out, however, there are other ways such PV covered parking lots could be leveraged, such as for charging customer-owned electric cars. This would presumably not only help improve store selection but also the time that customers spend in the store waiting for their EV to charge. Future work is needed in evaluating the best use of parking lot overhead space for solar electric generation. This study showed that such systems are technically viable, however, the second and more granular technical and economic analysis based on the specific electrical and thermal loads of an individual big box stores is necessary before deployment. Future work is needed to probe the economics of both the electric and thermal energy production. The economic results of such analysis will vary significantly between individual locations based on a number of factors including conventional energy costs, government incentives and disincentives, and regulatory costs. In particular the GHG emissions created by the CHP need to be carefully quantified compared to both conventional generation as well as new technologies that enable thermal loads to be covered by solar powered heat pumps. If a retailer could use the stranded asset of a parking lot to generate additional revenue from electricity sales to its neighbors not only could it garner additional good will in the community, but it would also stand to potentially realize significant economic savings itself from displaced electric and heating costs. Prior work has indicated that such hybrid systems do decrease costs, but future work is needed to quantify this for such parking-lot systems throughout North America. To quantify the full economic benefits future work is needed to simulate heating ventilation and air conditioning (HVAC) loads at the stores and to calculate the levelized cost of electricity of the hybrid system to compare to the retail rates provided by conventional utilities. In addition, as many of these facilities have large lighting loads they are in space cooling mode most of the year. Thus, depending on the thermal characteristics of the location, absorption chillers can be installed with CCHP (CCHP) which will help to recover the maximum heat ejected from the CHP into useful energy. This will help for cooling purpose during hot summer days, which can be the backup to PV module. This will help for further increasing the efficiency of the system, but may also effect the economics. Finally, although the CCHP run on gas is far from free of emissions, previous work has shown it can reduce fuel utilization up to 30%–35%, so future work should investigate the GHG emissions reduction potential of the hybrid microgrid system as compared to conventional electricity. With Ontario becoming the first North American government to eliminate coal-fired electricity generation and the Prime Minster Justin Trudeau announcing that Canada would achieve net-zero by 2050 the use
of any fossil fuel as the backup fuel for the CHP may no longer be viable. Thus, future work is also needed to model such systems based on the use of renewable fuels to run a CHP such as biomass.\textsuperscript{90} Lastly, other dispatch strategies\textsuperscript{91-93} for such large-scale CHP-based systems can be modeled for this system to determine the optimum dispatch strategy. When this future is complete along with the thermal model such systems can then be designed for specific stores and deployed using several business models depending on what makes the most sense for the retailer. For example, these systems could be built using a financing obtained via power purchase agreements.

4 | CONCLUSIONS

This study provides a new two-step simple method to determine appropriate sizing of PV + CHP + battery units for hybrid microgrids systems to match PV deployed in retail store parking lots. The results show that such hybrid PV, CHP, and battery microgrid systems are technically viable for providing all of the electrical needs of roughly 1000 people. These 350 households in the direct vicinity of a standard big-box retail store parking lot covered with a PV canopy can provide enough area for a 3.5 MW parking lot PV system. The PV is coupled with a 1 MWe CHP and 14 MWh battery bank to provide all of the electricity needs for 350 households. During December the average hourly electrical energy produced for 350 houses by solar, cogen, and battery are found to be 64.1, 48.23, 166.15 kWh, respectively indicating that with some additional energy efficiency and load shifting an even greater solar fraction could be obtained. In July the community is completely serviced by the PV and battery system. Future work is necessary to quantify the economic and environmental benefits of such a hybrid microgrid system.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

CONFLICT OF INTEREST

The authors have no conflict of interest relevant to this article.

AUTHOR CONTRIBUTIONS

Kunal Shah: Data curation; formal analysis; investigation; methodology; software; validation; visualization; writing-original draft; writing-review & editing. Dane George: Data curation; formal analysis; investigation; methodology; software; validation; visualization; writing-review & editing. Lukas Swan: Formal analysis; funding acquisition; investigation; methodology; resources; software; supervision; validation; writing-review & editing. Joshua M. Pearce: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing-original draft; writing-review & editing.

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