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City of Madison Microgrid Feasibility Analysis: Engineering Operations and Streets West

1600 Emil St and 1501 W Badger Rd

slipstream

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ACRONYMS

AVERT	Avoided Emissions and Generation Tool
BESS	battery energy storage systems
DER	distributed energy resource
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EV	electric vehicle
HVAC	heating, ventilation, and air conditioning
kW	kilowatt
kW_{dc}	direct current kilowatt
kWh	kilowatt-hour
MPGe	miles per gallon gasoline equivalent
MWh	megawatt-hour
NREL	National Renewable Energy Lab
NPV	net present value
NO_X	nitrous oxides
PSC	Public Service Commission
$PM_{2.5}$	particulate matter 2.5
SO_2	sulfur dioxide
PV	photovoltaics
V2G	vehicle to grid

EXECUTIVE SUMMARY

This study details the work of Slipstream in partnership with the City of Madison to assess the feasibility of establishing a microgrid at 1600 Emil St and 1501 W Badger Rd Streets, a site housing Streets West and Engineering Operations. This site provides key functions during emergencies including police and fire support functions, snow removal, road maintenance, sewer maintenance, and mapping and situational awareness services.

In addition to hosting critical infrastructure, the site already has several distributed energy resources which make it an ideal candidate for a microgrid. Namely, there are existing solar PV arrays totaling 209 kW, with an additional 219 kW planned for installation in 2022. There are also two back-up generators on site. Another key opportunity is the vehicle fleet; the site currently has over 230 vehicles, a fleet which the city plans to convert to 100% electric vehicles over the next five to 15 years.

The goals of the study were to evaluate integrating these components into a microgrid that would be cost-effective, increase resilience, and contribute to the City of Madison's emissions reduction goals. The specific research questions addressed were:

1. What are potential battery energy storage systems (BESS) configurations to meet needs at the site today?
2. As the vehicle fleet electrifies, how will those configurations perform?
3. What are the associated costs and benefits of each configuration?

The scenarios included for analysis were based on the expected timeline, charging needs, and critical charging profile of the fleet. Fleet electrification was divided into two phases (Phase 1 and Phase 2) depending on the expected availability of commercial versions of existing fleet vehicles. In addition, given the limited space available at the site for a BESS, the maximum BESS which can be accommodated was used as an upper bound. These two factors were used to develop four scenarios – fleet electrification phases 1 and 2 with no constraint on the battery size, and the same phases with a BESS specified at the upper limit of 10 MWh.

RESULTS OVERVIEW

Table 1 shows summary results for the base case and the four scenarios. As the load increases with no battery constraint, (moving from Phase 1 to Phase 2), the main difference in system operation is that more solar is used on site, reducing exports. When the maximum battery size is specified, the solar exports reduce further, and resiliency hours increase.

However, considering the emissions reduction and resiliency benefits puts these high upfront costs in context. The systems with a large battery show the greatest emissions reduction due to the ability of the BESS to use power from the grid at times when grid emissions intensity is lowest. In the case of the Phase 2 BESS scenario, the large load amplifies the impacts of the emissions reduction optimization to show the greatest benefit. By including the value of emissions savings, the Phase 2 BESS scenario achieves a positive NPV despite having the highest upfront costs.

Table 1. Summary results.

Scenario	Base case	Phase 1	Phase 2	Phase 1 BESS	Phase 2 BESS
Battery capacity (kW)	0	47	48	410	1,170
Battery size (kWh)	0	61	63	10,000	10,000
Generator energy (kWh)	533	672	0	719	300
Solar exported (kWh)	327,213	269,206	233,409	127,189	124,654
Initial capital costs	$0	$60,000	$61,600	$4,197,600	$4,786,500
Total cost	$122,200	$208,600	$211,000	$7,503,000	$8,210,400
Total energy benefits	$319,600	$274,400	$233,500	$388,900	$282,400
Health benefit	$0	$72,200	$73,500	$728,400	$1,796,700
CO_2 reduction (tons)	0	300	300	3500	8800
CO_2 reduction benefit	$0	$19,000	$19,000	$196,400	$488,500
Emissions benefit	$0	$91,200	$92,500	$924,800	$2,285,200
Resiliency (hours)	207	150	13	1,309	105
Resiliency benefit	$2,248,900	$2,746,700	$916,200	$2,746,700	$6,633,300
NPV with Emissions + Resiliency	$2,446,300	$2,903,700	$1,031,200	-$3,442,600	$990,500

Valuing resiliency causes an increase in the NPV across scenarios, with the most significant increase seen in the Phase 1 BESS scenario, where the 10 MWh battery provides the greatest average resiliency. In the Phase 2 BESS scenario, the significant increase in critical load causes a relative reduction in resiliency benefits.

Several recommendations and next steps were developed during the feasibility study, summarized below.

RECOMMENDATIONS

Given that the site is currently operational with several major projects underway or in planning stages, several recommendations address the existing infrastructure. First, the City should **develop a plan to electrically interconnect the three buildings at the site**. This interconnection is a key assumption of the analysis, as it enables the buildings to share loads and resources, enhancing the benefits that each asset can provide. Second, as new solar PV arrays are being installed, **microgrid-ready inverters should be specified**. Doing so will add an incremental cost to the inverters but will enable them to integrate seamlessly with the BESS. In addition, several of the existing inverters may also require upgrades or additional hardware to be able to integrate with the planned microgrid controller. Finally, given the important role that the BESS will play and the reality that space on site is limited, **we recommend performing a detailed site survey to establish a code-compliant BESS installation location**.

Several other recommendations for general microgrid planning were developed during the project. First, it is important to **prioritize data collection and start early**. The quality and quantity of primary data collected directly impacts the relevance and robustness of the results for the proposed microgrid. Key data to collect should cover the building energy loads (both electric and natural gas), vehicle mileage and usage patterns, historical operating and maintenance costs, and utility rates.

To achieve the city's emissions reduction goals, nearly all natural gas end uses will need to be converted to electric. This will add significant electric load, requiring larger batteries and PV arrays to meet critical demand at each site where a microgrid is implemented. Thus, it is important to **develop a detailed plan for electrification of natural gas end uses** to understand the impact on any proposed microgrids.

For the city-wide vehicle fleet, **we recommend implementing a unified smart-charging system, and exploring the possibility of using V2G to meet critical demand.** Smart charging infrastructure can enhance the ability of a microgrid controller to manage loads and sources, increasing the benefits of the microgrid while potentially reducing the size of BESS needed, saving on upfront costs. Similarly, V2G (or vehicle-to-grid) could allow non-critical vehicles to store power during outages for critical loads, further enhancing the microgrid's resiliency.

CONCLUSION

A microgrid at the Badger Rd and Emil St site can help meet several City of Madison goals: increase use of renewable energy, improve resiliency, reduce pollution and carbon emissions, and reduce energy costs. The results in this study highlight the various ways that the benefits of a BESS can be evaluated to justify the significant upfront cost, especially as electrification of the vehicle fleet increases the electric load that the microgrid must be able to meet.

Key barriers to implementation include the high cost of a BESS sufficiently sized to meet the needs of the site, and the fact that the total solar PV capacity on site is limited. Load management strategies, including smart charging and V2G, could be used to carefully manage the critical load and increase resiliency despite the limited PV capacity.

When considering the total cost of the system, it is critical to include resiliency and emissions benefits. With a BESS, the microgrid provides significant resiliency benefits when planning for a major outage on an annual basis. The BESS also provides environmental and health benefits by enabling the facility to use less power from the grid during times when grid emissions factors are highest. Accounting for the value of these benefits significantly increases the NPV of the proposed microgrid.

Based on these takeaways, we recommend that the City of Madison pursue a microgrid at the site with a BESS. Given that the fleet will be electrified over time, we recommend installing a small modular BESS, with the option to expand over time. This will enable the site to immediately take advantage of the benefits of a microgrid, while enabling staff to study the real-world performance and to make informed decisions about future expansions.

1 INTRODUCTION

As climate change normalizes extreme weather events, grid and community resiliency are put to the test. To respond to this growing need, the City of Madison is actively planning its resiliency efforts and increasing the resilience of critical city infrastructure, implementing renewable energy projects, and pursuing aggressive emissions reduction targets. With funding from the Wisconsin Public Service Commission (PSC) and in partnership with Slipstream, the City of Madison assessed the feasibility of establishing a microgrid at a site which provides key functions during emergencies including snow removal, road maintenance, sewer maintenance, police and fire support functions, and mapping and situational awareness services. This site also hosts over 200 vehicles, a fleet which the city plans to convert to 100% electric vehicles over the next five to 15 years.

The goals of the study were to evaluate integrating existing and planned distributed energy resources (DER) at the site into a microgrid that would cost-effectively provide for electric vehicle (EV) charging while increasing resilience for the city of Madison by providing back-up power at the site. Existing assets include several solar photovoltaic (PV) arrays and a natural gas generator. Additional PV arrays and a battery energy storage system (BESS) are planned for the near future.

The analysis considered the ability of the microgrid to provide continuous backup power for critical loads at the site while cost-effectively enabling EV charging. The specific research questions were:

1. What are potential BESS configurations to meet needs at the site today?
2. As the vehicle fleet electrifies, how will those configurations perform?
3. What are the associated costs and benefits of each configuration?

The report starts by providing project background and details on the City of Madison and the site. We then describe the methodology and results of the microgrid planning. The results highlight the tradeoffs between different system configurations to inform future microgrid planning, but a more in-depth analysis would be needed if the city decided to proceed with a microgrid installation. We provide a checklist of microgrid considerations for the site, as well as general recommendations for other sites that they city may consider converting to microgrids in the future.

1.1 BACKGROUND

The City of Madison is the second-largest city in Wisconsin, home to 255,000 people. The city has a goal for city operations to be emissions neutral by 2030. As part of that goal, Madison has been installing solar PV arrays at several of its buildings.[1] Most of Madison, including the proposed microgrid site, is served by Madison Gas and Electric (MGE) an investor-owned utility.

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[1] Progress towards this goal is documented here: https://www.cityofmadison.com/engineering/facilities/energy/solar-locations

The microgrid study focused on three adjacent city-owned facilities that already have solar PV and back-up generators on-site, shown in Figure 1.

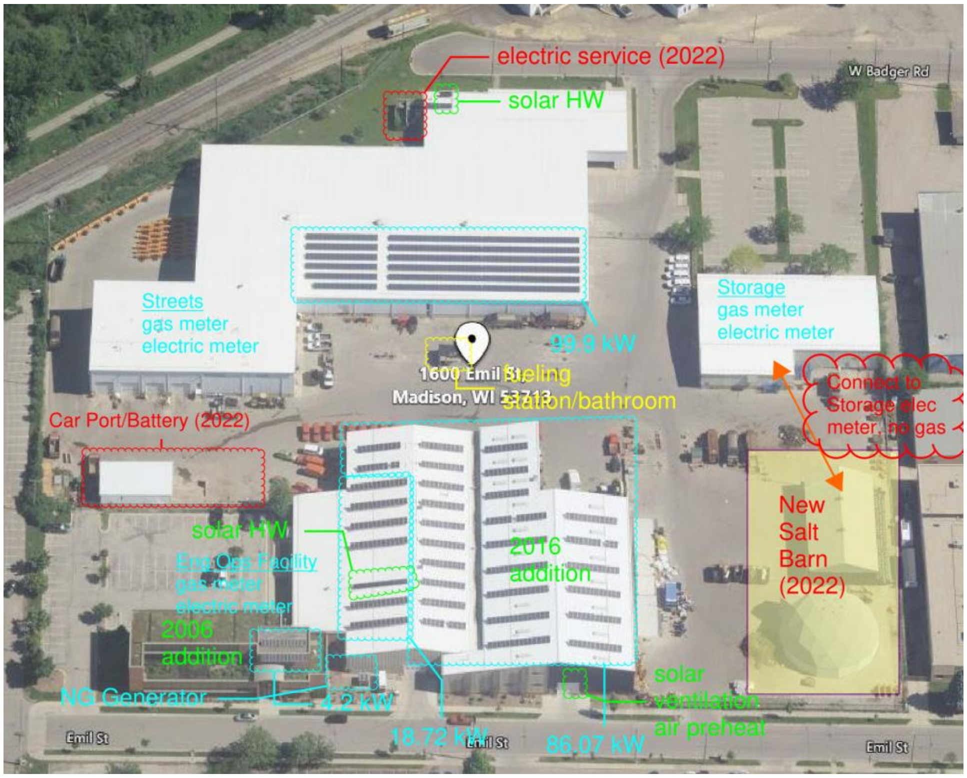

Figure 1. Site layout for Streets West and Engineering Operations showing proposed changes.

The facilities house Madison’s streets division and engineering operations and are city headquarters for several critical government functions: emergency support services, snow removal, road maintenance, and sewer maintenance. The facilities currently have 209 kilowatts (kW) of solar PV installed, with an additional 200 kW of additions planned through 2023, which would maximize the roof capacity at the site. Most of the inverters are compatible with SunSpec Modbus and could likely be integrated with any future microgrid. The site also has a newer 300-kW natural gas generator and an older 100-kW diesel generator, which is near end-of-life.

The site houses over 230 vehicles and gas-operated machines, including both heavy- and light-duty vehicles. The City of Madison plans to electrify as much of its fleet as possible over the next 10 years. This study analyzed how the expanded EV fleet with managed charging would impact the performance and configuration needs of the microgrid, both while grid connected and during outages.

2 METHODOLOGY

We conducted the feasibility study with a set of four analysis stages and ongoing stakeholder engagement. We started by identifying tools to evaluate microgrid system configurations, costs, and benefits. We evaluated seven tools and their ability to optimize assets and dispatch to meet the critical functions of the microgrid. We then collected energy, cost, technology, and site data to use as inputs in the analysis. Finally, we ran several initial scenarios through the selected analysis tool and compared the high-level results to identify a set of alternatives for the site. The final step was to summarize the associated costs and benefits for the final scenarios.

Figure 2 illustrates the four phases of analysis. The following section provides additional detail on the tool selection process and the data inputs utilized for the analysis.

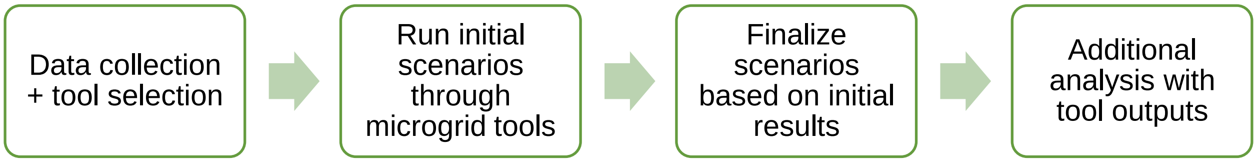

Figure 2. Feasibility study analysis.

2.1 STAKEHOLDER ENGAGEMENT

Stakeholder engagement was a critical, ongoing task throughout the study. The City of Madison developed a staff stakeholder group, which consisted of facility staff, city sustainability managers, and operations managers. The stakeholder group assisted with data collection efforts and provided essential feedback on the objectives of the microgrid and which scenarios were most feasible and in-line with city goals for renewable energy and resiliency. The stakeholder group was instrumental in answering critical questions, such as:

- What are the key functions vehicle fleet should be able to provide during outages or emergency events, and which vehicle types are critical to this?
- What near-term plans does the facility have for adding, upgrading, or modifying DERs?
- How does this site fit into larger city goals for renewable energy? Are there specific emissions or renewables targets the site needs to meet?

In addition to the staff stakeholder group, we also engaged the local utility in discussions. Involvement of the utility was essential to understand any size restrictions, applicable financial rates and benefits, and the utility’s interest in co-ownership models.

2.2 ANALYSIS TOOLS

Through a literature review, we identified seven tools for microgrid and DER scenario analysis.[2] Once the candidate tools had been identified, we developed a critical features matrix to use

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[2] Krah, “Behind-the-Meter Solar + Storage Modeling Tool Comparison”; Tozzi and Jo, “A Comparative Analysis of Renewable Energy Simulation Tools.”

when evaluating each tool. The features that were evaluated and the desired criteria are shown in Table 2. Features are listed roughly in order of importance to the analysis.

Table 2. Microgrid analysis tool critical features and criteria for each site.

Feature	**Madison requirement**
Backup generator	Model the existing natural gas generator
Resiliency analysis	Satisfy minimum load and duration for backup coverage
Existing PV analysis	Model existing and planned PV capacity
Custom load profile	Model a known hourly load profile
Load growth	Model load growth due to fleet electrification
BESS modeling	Optimize for BESS capacity, duration, and dispatch. Consider BESS degradation.
Hourly results	Provide hourly dispatch results to allow for supplemental financial and environmental analysis
Optimization	Optimization algorithm should select component size and dispatch to maximize life-cycle benefits
License	Free and open-source products preferred to allow for dissemination of results across stakeholders.

Next, we reviewed the literature about these tools and consulted documentation and user forums to determine whether each tool met these requirements. We qualitatively analyzed each tool to determine if the requirement was fully met, partially met, or not met, represented through filled, half-filled, and unfilled Harvey balls, respectively (Table 3). In some cases, we could not determine if a requirement was met, or we ended our evaluation after identifying that a tool did not meet the more critical requirements. In these cases, the associated cell in the matrix is left blank.

Table 3. Critical feature matrix for the eight microgrid analysis tools considered.

Critical features	**DER-VET**	**REopt**	**HOMER**	**DER-CAM**	**SAM**	**ESyst**	**MDT**
Back-up generator	◐	◐	●	●	○	○	○
Resiliency	●	●	●	◐	○	○	●
Existing PV	●	●	●	●	◐	◐	◐
Custom load profile	●	●	●	◐	●	●	◐
Load growth	◐	○	●	-	●	-	-
BESS modeling	●	◐	●	◐	●	●	-
Hourly results	●	●	●	○	●	○	-
Optimization	◐	●	●	●	◐	○	●
License	●	●	○	◐	●	◐	◐

Based on our analysis, we decided to proceed with REopt due to its ability to meet each of the priority features and the open-source license and API (application programming interface, allowing the use of a scripting language to programmatically run scenarios). Figure 3 illustrates the key inputs and outputs from REopt.[3] The user inputs the technology of interest, any resiliency or environmental goals, energy cost data, and a custom load profile. The tool then finds the least-cost option that satisfies the goals and provides system size, system financial, and resiliency outputs. The least-cost option is based on net present value (NPV) which is calculated over a 25-year lifetime.

To model resiliency, the tool requires the user to input the length and timing of an outage the optimal system should be able to withstand (e.g., June 19 from 1 to 5 pm). The tool then finds the least-cost option system that can withstand an outage at that time while still providing the load required. After the tool finds the least-cost option for that specific constraint, it evaluates resiliency (or length of outage the system could sustain) at each hour of the year.

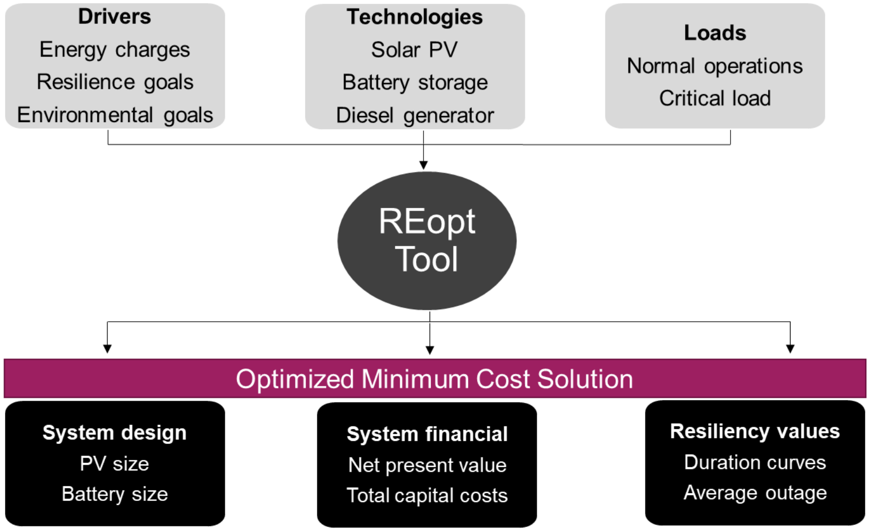

Figure 3. REopt optimization method.

2.3 OPTIMIZATION INPUTS

The following sections describe the data and methodology used for each input into REopt.

2.3.1 Facility load profiles

The site consists of three buildings with dedicated electric services from MGE, as well as several smaller outbuildings which are electrically connected to the others. Table 4 includes summary statistics for the three buildings on the main campus, as well as the Library Service Center which is included in a sensitivity (see Section 3.4.1).

The coincident peak demand for the main site was 173 kW in 2021. With the library included, the peak demand would have been 184 kW.

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[3] Anderson et al., "REopt Lite User Manual."

Table 4. Summary of load and solar attributes by building.

Building	**Engineering**	**Streets West**	**Streets Storage**	**Library Service Center**
Address	1600 Emil St	1501 W Badger Rd	1501 W Badger Rd	1301 W Badger Rd
2021 consumption (kWh)	274,903	258,004	29,163	104,449
2021 peak demand (kW)	117	65	10	31
Existing solar capacity (kW$_{dc}$)	108.99	99.90	-	53.00
2021 solar production (kWh)	122,165	116,237	-	61,167
Additional planned solar (kW$_{dc}$)	35.42	198.66	40.00	-
Current ICEV fleet	179	43	-	-
Current EV fleet	6	2	-	-

2.3.2 Existing and planned solar PV

The first solar array was installed on the site in 2008, with three arrays added since then, one currently under construction, and two more planned. Once the planned capacity is added, the site's limit for PV capacity will likely be reached, as all available roof space will have been utilized. Details of the arrays are included in Table 5.

Table 5. Selected details of existing and planned solar arrays.

Building	**Array size (kW$_{dc}$)**	**Year installed**	**Inverter**	**SunSpec Modbus compatibility**
Engineering	4.20	2008	Fronius IG-4500-LV	With Fronius Datamanager.
Engineering	18.72	2013	SMA SB10000US-10	Native.
Engineering	86.07	2018	SolarEdge SE33.3KUS, SE20KUS with P730 optimizers.	With firmware version 3+. Older versions can be upgraded.
Engineering	35.42	2023	TBD	TBD
Streets	99.90	2017	Fronius Primo 15.0-1	Native.
Streets	198.66	2022	SolarEdge SE100KUS, SE66.6KUS with P860 or P960 optimizers.	With firmware version 3+. Older versions can be upgraded.
Storage	20.00	2022	TBD	TBD
Salt barn	20.00	2022	TBD	TBD
Main site total	**482.97**			
Library Service Center	53.00	2018	Fronius Primo 11.4-1 and Symo 10.0-3	Native.
Combined total	**535.97**			

We confirmed that all installed and planned inverters are compatible with SunSpec Modbus, either natively, with a firmware upgrade, or with an external hardware upgrade. This will be a minimum requirement for integration with any future microgrid controller, enabling the controller to utilize the voltage regulation, power factor management, and export limiting capabilities of each inverter.[4] However, all the existing inverters are grid-tied, meaning they require a stable grid connection to produce power. While a BESS could likely provide a stable enough signal to support operation of these inverters, it may be necessary to include multi-mode inverters (either through expansion or replacement) which would be capable of coordinating with a microgrid controller to establish a grid signal during outages.

Due to the total planned capacity, the site will not be eligible for net metering (MGE's limit is 100 kW) but will be able to sell excess solar generation to the grid at wholesale rates.

2.3.3 Electric vehicle charging needs

A primary function of the site is vehicle storage, with over 230 vehicles, including passenger vehicles, light- to heavy-duty trucks, and miscellaneous equipment such as excavators and tractors. Currently, only eight of the vehicles on site are electric vehicles. However, the city is on track to fully electrify all light- and medium-duty vehicles by 2027. There are also plans to electrify as many heavy-duty vehicles as possible by 2030, based on the types of heavy-duty EVs that are currently on the market. The rest of the heavy-duty vehicle fleet would then be electrified as soon as commercial versions of each vehicle type are available.

We used this timeline and the inventory of current vehicles and mileage records to split electrification into two phases: Phase 1 vehicles are ones that will be electrified in the near-term (5 to 10 years) and Phase 2 vehicles are ones that will be electrified in the long-term (10+ years). Phase 1 included all passenger vehicles, pickup trucks, and a small set of miscellaneous equipment (117 vehicles total), while Phase 2 included all heavy-duty vehicles and the rest of the miscellaneous equipment (an additional 105 vehicles). Eight electric vehicles are already housed at the site. The inventory (along with expected kWh needed to power each vehicle type) is in Table 6. "Refuse truck" includes seven Vactor trucks in addition to traditional refuse trucks.

The MPGe ratings by vehicle type are from AFLEET.[5] For the miscellaneous equipment, we simply used a conversion from gallons of gasoline to kWh, as information about the efficiency of most equipment types was not readily available. While this is a conservative estimate (as electrified versions of each type of equipment are likely to be more fuel efficient), fuel use for this equipment is less than 5% of the annual total for the fleet, and thus is not likely to significantly affect the analysis. The total vehicle counts and expected energy consumption by phase is summarized in Table 7. Note that the totals shown in Table 7 do not exactly match the sum of the values in Table 6, as they are instead derived from the simulation results described in the following section.

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[4] For more information, visit https://sunspec.org/sunspec-modbus-specifications-2/

[5] Argonne National Lab, "AFLEET Tool."

Table 6. Fleet electrification phases, vehicle quantities, and energy consumption – by vehicle type.

Vehicle type	MPGe	Quantity	Annual mileage (per vehicle)	Annual kWh (total)
		Phase 1		
Pickup	57.3	29	9,015	153,758
Pickup (large)	37.8	29	15,000	387,817
SUV	69.5	6	7,247	21,084
Sedan	106.2	15	4,583	21,815
Van	29.1	13	13,500	203,242
Misc. truck	16.0	16	12,000	404,400
Misc. equipment	-	9	-	7,229
		Phase 2		
Dump truck	13.7	18	96,300	236,884
Refuse truck	4.8	14	322,000	2,260,708
Misc. equipment	-	73	-	428,047

Table 7. Fleet electrification phases, vehicle quantities, and energy consumption – total.

Load profile	EVs	Additional kWh	Total kWh	Load growth vs baseline
Base building load	8	556,000	556,000	-
Phase 1	117	1,231,000	1,787,000	323%
Phase 2	105	3,104,000	4,891,000	985%
TOTAL	**230**	**4,891,000**	**-**	**-**

2.3.3.1 Normal operations charging profile

To develop a daily charging profile for the two phases, we adapted the model developed in Borlaug et al. 2021, which modeled three different charging strategies for three different fleet types. Based on miles traveled and idle time per day, the passenger vehicles and trucks were matched to Fleet 1 (with a consistent daily schedule), while miscellaneous equipment was matched to Fleet 2, with a more sporadic scheduling including long periods where equipment was used rarely.

For charging strategies, we assumed a minimum power charging strategy (where vehicles charge slowly for the duration of time while they are off shift) for most vehicles, with an immediate charging strategy for 10% of vehicles to cover those which must be always close to a full charge to accommodate city operational needs. Once the fleet types and charging strategies were selected, we ran the code (included with the publication) using the vehicle quantities and average efficiencies and scaling the annual vehicle mileage of the model fleets to match the actual fleet. Figure 4 shows the resulting hourly charging profile for the two phases.

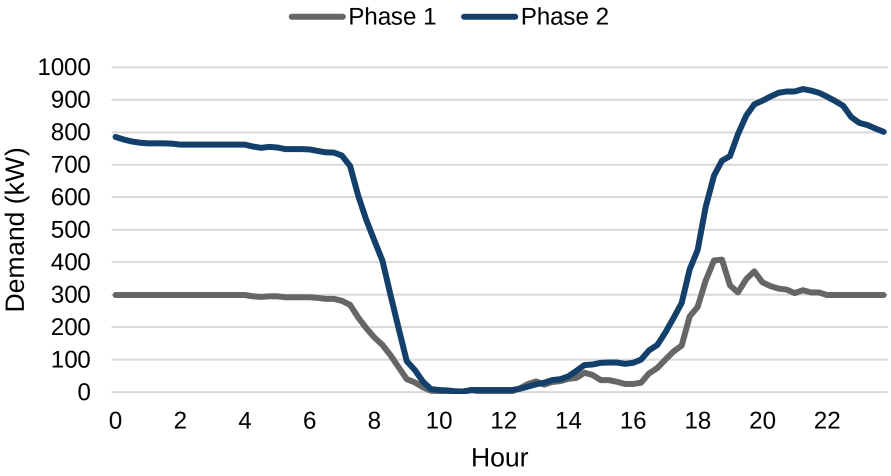

Figure 4. Electric vehicle average hourly load profiles: Phase 1 and 2 electrification.

There remains uncertainty around the final load profile, as the fleet electrification schedule is still being developed, and in some cases fully electric replacements are not yet available for vehicles in the fleet. These assumptions are considered a best guess and have been provided to City staff to serve as a baseline for updating the load profiles as the electrification schedule is updated.

2.3.3.2 Critical operations charging profile

In addition to the full building and EV charging load, it was important to understand the critical energy load profile needed during emergency situations or power outages. Because the current facility has a natural gas generator which can provide 100% back-up power, the entire facility load is considered critical. With only eight of over 200 vehicles housed at the site being electric, there is no data available to determine exactly what share of the fully electrified fleet should be considered critical in the modeling.

Ultimately, we applied Clean Coalition's VOR123 methodology of define Tier 1, Tier 2, and Tier 3 critical loads.[6] While this methodology was developed for categorizing facility loads, our stakeholder discussions led to the conclusion that there was no clear way to determine which of the vehicles should be considered critical in an annual model given the varied nature of emergencies the City needs to anticipate and the diversity of vehicles, and their functions, located at the site.

Instead, stakeholders decided to divide the entire EV charging load into three tiers. Given the robustness of the VOR123 methodology for facility loads, we determined that the same criteria and general guidelines could be applied to a vehicle fleet in the absence of available data and studies on this specific topic. As plans for completing the microgrid go forward, the city will need

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[6] Lewis, "A Revolutionary Way to Easily Value Resilience for Any Facility."

to embark on a detailed study of how different vehicles are used in different types of emergencies to be able to properly size and operate the microgrid.

Under the VOR123 methodology, 10% of all load is considered critical or life sustaining (Tier 1), 15% is considered priority (Tier 2), and the remaining 75% is considered discretionary (Tier 3). Given the nature of the facility and the current requirement to provide 100% backup power to the facility loads during outages, we assume that all Tier 1 and 2 vehicle functions must also be available during outages.

During phase 1 of vehicle electrification, this need could be met with a mix of the EVs and ICEVs which would be operational at that point. Thus, we assume that 10% of electric charging needs would be critical, with the remaining 15% served by ICEVs. For phase 2, all the Tier 1 and 2 needs must be met with EVs, as no ICEVs will remain in the fleet at this time – thus 25% of charging demand would be critical at this point. On average, each vehicle in the fleet travels 44 miles per day. With critical charging limited to 25%, every vehicle would be able to travel 11 miles per day, or 25% of vehicles could travel 44 miles per day.

Note, this does not directly translate to the fleet only being able to operate at 15% or 25% capacity, as each vehicle in the fleet would have a battery capacity able to sustain more than one shift of normal operations given current mileage patterns. Nevertheless, as the demand for operating vehicles may increase during an emergency, it will be important to monitor the state of charge of each vehicle to prioritize how each is operated and charged, especially during extended power outages.

2.3.3.3 Other costs and benefits

Several aspects of vehicle electrification are not considered in the optimization analysis, such as the upfront cost of electric vehicles and lower total cost of ownership. While the capital cost of an EV fleet is outside the scope of this study, below we provide rough estimates of operating cost savings due to reduced use of gasoline and diesel and reduced maintenance costs.

Using Madison’s fleet inventory and annual mileage records, combined with average fuel economy ratings from the Department of Energy’s Alternative Fuels Data Center [7], we calculated that the fleet of vehicles at the site uses over 240,000 gallons of gasoline and diesel fuel per year. Using an average fuel price over the last 12 months of $3.72 per gallon,[8] this amounts to over $900,000 in annual fuel expenditure. In contrast, our analysis indicates that if fully electrified, the fleet would use roughly 4,125,000 kWh per year. Even at the peak electric rate ($0.104 per kWh, see Section 2.3.5), this represents a cost of just under $430,000 per year, for a savings of greater than 50% annually.

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[7] US DOE, “Alternative Fuels Data Center.”

[8] US EIA, “Midwest (PADD 2) Gasoline and Diesel Retail Prices.”

A recent report from Argonne National Labs indicates that on average, electric vehicles (EV) have annual maintenance costs roughly 40% lower than internal combustion engine vehicles (ICEV).[9]

2.3.4 Resiliency inputs

There are two resiliency inputs of interest for this analysis: (1) length of outage for the system to withstand and (2) monetary value to assign to increased resiliency.

2.3.4.1 Length of outage

To identify outage lengths of interest, we started by reviewing existing data on the length of power outages over the past several years. Through this research, we identified two types of outages: routine outages and major disturbances/unusual occurrences. We reviewed MGE's data on typical outages[10] and the Energy Information Administration's data on major outage events across the Midwest over the last three years to understand key characteristics of each.[11] Table 8 illustrates these characteristics for each outage type.

Routine outages are more common and are shorter in length and major outages occur less frequency but are often 1 to 5 days in length. While the data tells us that outages occur year-round, the Department of Energy reports that in Wisconsin, June is month with the highest frequency of outages.[12] Based on this data, we utilize outages in June as the constraint in each of the scenarios and tested varying outage lengths.

Table 8. Outage event characteristics.

Metric	Routine Outage	Major Disturbance
Frequency	Couple times a year	Once every few years
Impact	Low	High
Duration	2 hours	1 to 2 days and up to 5 days
MGE	< 1 hour	-
Time of Year	Year round	March to November

2.3.4.2 Resiliency monetary value

Installation of microgrids has resiliency benefits, which often make the difference between the system being cost-effective or not.[13] Although these benefits are widely acknowledged, there is not a standardized way to monetize the benefits.[14] Previous methods to quantify the value

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[9] Burnham et al., "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains."
[10] MGE, "2021Corporate Responsibility and Sustainability Report."
[11] US EIA, "Electric Power Monthly - U.S. Energy Information Administration (EIA)."
[12] US DOE, "State of Wisconsin Energy Sector Risk Profile."
[13] Anderson, Hotchkiss, and Murphy, "Valuing Resilience in Electricity Systems."
[14] Rickerson, Zitelman, and Jones, "Valuing Resilience for Microgrids: Challenges, Innovative Approaches, and State Needs."

include willingness-to-pay surveys and tools to help facilities develop bottom-up monetary estimates for lost time spent on critical functions.

There are limited studies that quantify the more human benefits from microgrids. The best reference for these values is a study from Lawrence Berkeley National Lab that includes estimates from willingness-to-pay studies for the residential and commercial sector.[15] Table 9 illustrates the study's findings on the value of resiliency across outage lengths and sectors.

For our purposes, we utilize the residential values as the commercial values assume lost productivity from commercial or industrial processes. The main limitation is that the values do not extend past outage lengths of 16 hours.

Table 9. Value of resiliency across outage lengths.

Cost per kW	Momentary	0.5 hour	1 hour	4 hours	8 hours	16 hours
Large Commercial	$15.9	$18.7	$21.8	$48.4	$103.2	$203.0
Small Commercial	$187.9	$237.0	$295.0	$857.1	$2,138.1	$4,128.3
Residential	$2.6	$2.9	$3.3	$6.2	$11.3	$21.2

2.3.5 Cost variables

Upfront and ongoing costs of the microgrid and battery technology, as well as the energy, wholesale and demand charge rates are a significant influence on the identification of a least-cost solution. Table 10 details the upfront costs for the BESS, including both the storage capacity cost and power capacity cost, and the 10-year replacement cost.[16]

Table 10. BESS system costs – upfront, operations and maintenance and replacement.

Variable	Input	Source
Storage capacity cost ($/kWh)	$388	NREL + Lazard
Power capacity cost ($/kW)	$775	NREL + Lazard
Storage capacity replacement cost ($/kWh)	$220	NREL + Lazard
Power capacity replacement cost ($/kW)	$440	NREL + Lazard

Table 11 lists the utility and wholesale rates utilized in the analysis (the table shows a simplified summary as the actual rate schedules include three different peak periods). Under MGE's rate structure, the most cost-effective option at the site is the time-of-day rate, which the site is using currently. The peak demand for the site is currently less than 200 kW, but as the fleet electrifies the demand will increase above 200 kW, meaning that the rate will change from CG-4 to CG-2, with higher demand charges and lower energy charges. As the limit for net metering is 100 kW

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[15] Sullivan, Schellenberg, and Blundell, "Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States."

[16] Ray, "Lazard's Levelized Cost of Energy Analysis—Version 15.0"; Feldman and Margolis, "Fall 2021 Solar Industry Update"; Anderson et al., "REopt Lite User Manual."

and the planned capacity is nearly 500 kW, we utilized wholesale rates for sale of excess solar. We also include the fixed demand charge to account for potential peak demand savings.

Table 11. Current utility and wholesale energy rates.

Variable	**Timing**	**Rate CG-4**	**Rate CG-2**
Demand limit (kW)	Annual	20 to 200	Over 200
Energy rate ($/kWh)	On-peak	$0.104	$0.102
	Off-peak	$0.076	$0.071
Demand charge ($/kW daily)	Summer	$0.427	$0.475
	Winter	$0.349	$0.392
Wholesale rate ($/kWh)	On-peak	$0.047	
	Off-peak	$0.034	

We assume a 2.5 percent escalation rate for operations and maintenance costs, a 2.3 percent increase in electricity rates, and utilize a 3 percent discount rate.

2.3.6 Emissions data and prices

We utilized hourly emissions data to estimate the impact of each system on the environment. The emissions data include carbon dioxide emissions and criteria pollutants, including nitrogen oxides, sulfur dioxide, and particulate matter. The hourly emissions data for each comes from EPA's Avoided Emissions and Generation Tool (AVERT), which models marginal emissions rates for the region based on historical dispatch data.[17] The data assumes a gradual greening of the grid and reduces emissions factors by 1.1 percent annually.[18]

To estimate the monetary impact of the emissions savings, we apply cost per ton estimates to each. Table 12 lists the cost per ton for each of the major pollutants.[19] The air quality pollutants have significant costs per ton as the reduction in emissions has the potential to prevent premature death, which is valued at roughly $9 million. The cost for each is assumed to increased gradually over the analysis lifetime.

Table 12. Pollutant costs per ton.

Pollutant	**Cost per Ton**	**Source**
Carbon dioxide	$51	Federal value
Nitrogen oxides	$19,542	CACES EASIUR model
Sulfur dioxide	$40,551	CACES EASIUR model
Particulate matter	$139,804	CACES EASIUR model

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[17] US EPA, "AVoided Emissions and GeneRation Tool (AVERT)."
[18] Anderson et al., "REopt Lite User Manual."
[19] Interagency Working Group on Social Cost of Greenhouse Gases, "Technical Support Document: Social Cost of Carbon, Methane,"; Heo, Adams, and Gao, "The Estimating Air Pollution Social Impact Using Regression (EASIUR) Model."

2.3.7 BESS constraints

The site has limited space for a battery energy storage system – two 40-foot storage containers are likely the largest which could be installed, which would support a 10 megawatt-hour (MWh) system.[20] For the analysis we allowed the BESS to be charged from the from the grid as needed, to ensure sufficient energy availability for covering outages.

REopt constrains the BESS to a minimum state of charge of 20%, as discharging the battery below 20% on a regular basis would reduce the lifespan.[21]

Lithium-ion batteries are available in a wide range of power to energy ratios,[22] though in practice the choices would be limited as these are dependent variables. However, to allow REopt the flexibility to optimize both variables, we only applied a constraint to the energy variable.

2.3.8 Generator metrics

By default, REopt assumes that generators are diesel-fueled. As a result, variables such as efficiency, cost, and emissions need to be provided per gallon of diesel. Because the generator at the site is natural gas-fueled, these inputs had to be converted from per therm values to the equivalent per gallon values. This is done be scaling the heat content of a gallon of diesel fuel (137,381 Btu [23]) to the heat content of a therm or cubic foot of natural gas (100,000 Btu and 1,037 Btu, respectively). Emissions factors for natural gas combustion are sourced from AP-42, the EPA's Compilation of Air Pollution Emissions Factors.[24] The final values used in the optimization are provided in Table 13.

Table 13. Natural gas generator parameters converted from diesel equivalents.

Metric	Diesel generator units	Natural gas generator value	Natural gas generator equivalent
Fuel cost	\$/gal	\$0.570/therm	\$0.783
Fuel efficiency	gal/kWh	12.249 ft^3/kWh	0.092
CO_2 emissions	lb./gal	120,000 lb. /10^6 ft^3	16.162
NO_x emissions	lb./gal	0.099 lb./MMBtu	0.014
SO_2 emissions	lb./gal	0.6 lb. /10^6 ft^3	8.081×10^{-5}
PM2.5 emissions	lb./gal	7.6 lb. /10^6 ft^3	0.001

The other critical parameter for generator modeling is the minimum load. The generator was constrained to run with a minimum load of 50%, as extended operation at lower loads can decrease the life of the generator and cause maintenance issues, unplanned shutdowns, and increased emissions.[25]

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[20] Fu, Remo, and Margolis, "2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark."
[21] Anderson et al., "REopt Lite User Manual."
[22] Dechent et al., "ENPOLITE."
[23] US EIA, "British Thermal Units (Btu)."
[24] US EPA, "AP-42."
[25] Jabeck, "The Impact of Generator Set Underloading."

2.4 SCENARIO SELECTION

As an existing facility with existing distributed energy resources and a planned electric vehicle fleet, several assumptions are already included in the base case, limiting the scenario selection process. First, the three electric services which exist on the site will be merged into a single service, allowing all buildings to share loads and resources. Second, the existing 300 kW natural gas-burning generator will remain and is sufficiently sized to support the full building load today (prior to additional fleet electrification). Third, the maximum solar capacity on site has been calculated as 483 kW, all of which will be installed prior to any microgrid implementation work.

With these constraints in mind, we analyzed four scenarios to understand the range of possibilities for the facility as the fleet is electrified, compared to the base case with only the existing facility load. As the fleet electrifies, a larger portion of the load will become critical to operations during outages. Scenarios are modeled first with an upper limit on storage capacity, then with a fixed capacity of 10 MWh, to understand the range of options between these two extremes. Table 14 lists the inputs that vary between the scenarios. Note that the outage coverage constraint is removed in Scenarios 3 and 4 as there is no solution possible within the given constraints that would guarantee coverage of any power outage, due to the significant increase in load.

Table 14. Scenarios and key inputs.

Inputs	Base case	Phase 1	Phase 1 BESS	Phase 2	Phase 2 BESS
Normal load profile	Facility	Facility Phase 1	Facility Phase 1	Facility Phase 1 Phase 2	Facility Phase 1 Phase 2
Critical load profile	Facility (100%)	Facility (100%) Phase 1 (10%)	Facility (100%) Phase 1 (10%)	Facility (100%) Phase 1 (25%) Phase 2 (25%)	Facility (100%) Phase 1 (25%) Phase 2 (25%)
Utility rate	CG-4	CG-2	CG-2	CG-2	CG-2
Battery constraint	<10 MWh	<10 MWh	=10 MWh	<10 MWh	=10 MWh
Climate and health objective	False	True	True	True	True
Outage coverage constraint	24 hours	24 hours	24 hours	None	None
Peak demand (kW)	173	517	517	1,369	1,369
Annual kWh	556,000	1,787,000	1,787,000	4,891,000	4,891,000

3 RESULTS

Table 15 illustrates the performance outputs for the base case and the four alternative scenarios. As the load increases with no battery constraint, (moving from Phase 1 to Phase 2), the main difference in system operation is that more solar is used on site, reducing exports. When the maximum battery size is specified, the solar exports reduce further, and resiliency hours increase. However, the high capital cost of the battery causes the net present value (NPV) to be negative. The NPV accounts for the costs and benefits of grid and solar energy only; factors such as health impacts, carbon emissions, and avoided outage costs are not included in these values. As the City of Madison reviews these results and plans for the future of the microgrid at the site, these factors, along with BESS financing options, will need to be considered.

Table 15. Results summary.

Scenario	Base case	Phase 1	Phase 2	Phase 1 BESS	Phase 2 BESS
BESS capacity (kW)	-	47	48	410	1,170
BESS energy (kWh)	-	61	63	10,000	10,000
Initial capital costs	-	$60,000	$61,600	$4,197,600	$4,786,500
Net present value	$197,400	$65,800	$22,500	-$7,114,100	-$7,928,000
Simple payback	-	0.2	0.3	21.3	>25
Solar energy exported (kWh)	327,200	269,200	233,400	127,200	124,700
Generator energy (kWh)	533	672	0	719	300
Total renewable	102%	32%	12%	30%	11%
Lifecycle CO_2 emissions (tons)	98	23,500	83,500	20,300	75,100
Emissions reduction	-	1%	1%	15%	11%
Resiliency hours (Average)	207	150	13	1,309	105

The following sections will explore the financial and resilience impacts, additional system benefits, and two sensitivities.

3.1 FINANCIAL IMPACT

The financial impact of each scenario is provided in Table 16. The only upfront cost considered in the optimization analysis is the BESS, as the solar PV, load management, and microgrid controller costs are the same across scenarios. REopt assumes a full battery replacement at 10 years, as the functional capacity of the battery would degrade over this time. While 10-year replacement is the simplest BESS management strategy, other strategies such as augmentation, oversizing, or modular implementation are also possible and may result in reduced total costs.[26]

All energy and demand savings are provided by the optimized dispatch of the BESS. Export credits are a function of how much excess solar generation is sold back to the grid.

As the size and capacity of the battery increase, the energy savings also increase, as the battery can shift the times during which energy from the grid is used. Yet, this comes at the cost of increased demand charges – the high battery capacity (over 400 kW) results in significant demand charges when the battery must recharge from the grid.

Table 16. Financial impacts of each scenario: costs and benefits.

	Base case	Phase 1	Phase 2	Phase 1 BESS	Phase 2 BESS
BESS cost	$0	$60,000	$61,600	$4,197,600	$4,786,500
PV O&M	$122,200	$122,200	$122,200	$122,200	$122,200
BESS replacement	$0	$26,400	$27,200	$3,183,200	$3,301,700
Total Cost	**$122,200**	**$208,600**	**$211,000**	**$7,503,000**	**$8,210,400**
Energy Savings	$0	$10,100	$10,000	$306,600	$306,900
Demand Savings	$0	$2,900	$1,600	-$43,900	-$142,500
Export Credits	$319,600	$261,400	$221,900	$126,200	$118,000
Total Benefits	**$319,600**	**$274,400**	**$233,500**	**$388,900**	**$282,400**
NPV	**$197,400**	**$65,800**	**$22,500**	**-$7,114,100**	**-$7,928,000**

3.2 RESILIENCY IMPACT

Fundamentally, the resiliency impact is a function of the load and the available backup power. Figure 5 illustrates that as the load increases from the base case to phase 1 and phase 2, the probability of surviving longer outages decreases. As a BESS is added, the probability again increases. The generator on site is currently sized at 300 kW, which is more than sufficient for the base case with a peak demand of 173 kW. But because phase 1 has a peak demand of 517 kW, and phase 2 has a peak demand of 1,369 kW the generator is less capable of contributing to outage survivability as the load increases with the fleet electrification efforts.

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[26] Shin and Hur, “Optimal Energy Storage Sizing with Battery Augmentation for Renewable-Plus-Storage Power Plants”; EPRI, “Energy Storage, DER, and Microgrid Project Valuation: EPRI DER-VET Analysis in Action.”

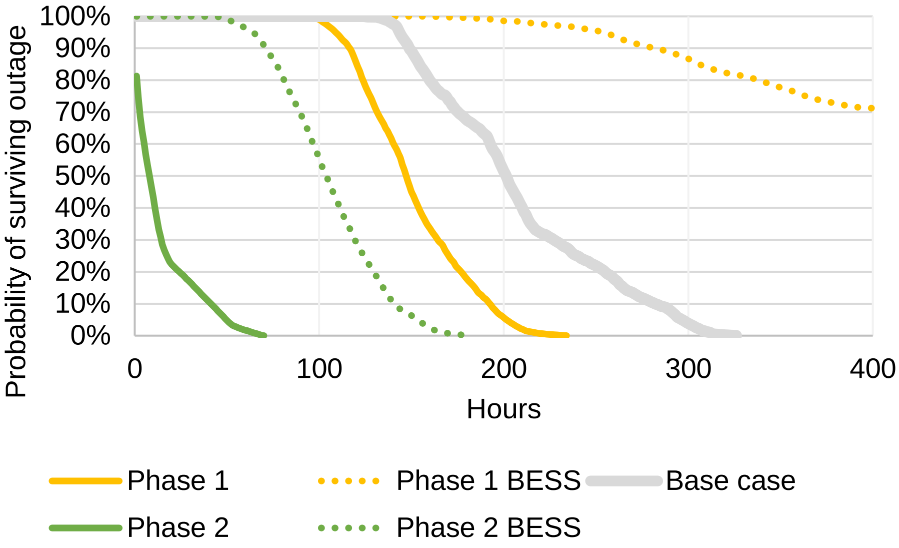

Figure 5. Outage survivability with existing and planned DERs

Figure 6 illustrates how resilience varies over the course of the year. The figure uses data from the Phase 2 BESS system, but the pattern is similar for all systems. Outage survivability is greatest during the spring and summer due to increased solar availability and lowest during the winter.

Figure 6. Rolling average resilience for Phase 2 BESS system

3.3 ADDITIONAL BENEFITS

A microgrid at the proposed site would provide significant monetary benefits beyond the energy, demand, and export savings. The benefits include the monetary value of resiliency, and the societal benefits of reduced carbon and criteria pollutant emissions. This section will highlight those benefits and show how the inclusion of the benefits impact NPV.

3.3.1 Resiliency monetary value

The monetary value of resiliency is calculated by taking the average hourly critical load multiplied by the average outage length and the deemed value of resiliency for an outage of that length. Because some scenarios can provide backup for significantly longer than expected outage durations, the outage length has been capped at four days (96 hours) for the resiliency value calculation. The value is then applied to any year in the project's lifetime when an outage is expected to occur and discounted back to present value.

The lifetime savings for resiliency depend directly on the frequency of emergency events and outages. As these outages are irregular in nature, there is no way to know how often the outages will occur during the lifetime of the system. However, research does show that outages are expected to increase in frequency as extreme weather events increase and as the grid faces generation shortages.[27]

Table 17 lists the resiliency monetary value for different outage frequencies across the system lifetime.

Table 17. Monetary value of resiliency: comparisons depending on outage frequency.

Metric	Base case	Phase 1	Phase 2	Phase 1 BESS	Phase 2 BESS
Critical load (kW)	63	78	187	78	187
Resiliency hours	207	150	13	1,309	105
Outage frequency	***Value of resiliency***				
One year	$2,248,900	$2,746,700	$916,200	$2,746,700	$6,633,300
Two years	$1,077,400	$1,316,000	$439,000	$1,316,000	$3,178,000
Five years	$423,600	$517,400	$172,600	$517,400	$1,249,400
Ten years	$167,600	$204,700	$68,300	$204,700	$494,400
Once ever	$85,400	$104,300	$34,800	$104,300	$251,800

Utilizing the monetary values for an outage occurring every year, Table 18 shows the NPV for each system when the value of resiliency is included. Valuing resiliency causes an increase in the NPV across scenarios, with the most significant increase seen in the Phase 2 BESS scenario, where the combination of the 10 MWh battery and the higher critical load provides the greatest resiliency value..

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[27] Robert Walton, "MISO Prepares for 'worst-Case Scenarios,' Heads into Summer with Insufficient Firm Generation"; Rickerson, Zitelman, and Jones, "Valuing Resilience for Microgrids: Challenges, Innovative Approaches, and State Needs."

Table 18. Resiliency monetary value impact on net present value.

	Base case	Phase 1	Phase 2	Phase 1 BESS	Phase 2 BESS
Total cost	$122,200	$208,600	$211,000	$7,503,000	$8,210,400
Energy benefits	$319,600	$274,400	$233,500	$388,900	$282,400
NPV without resiliency	**$197,400**	**$65,800**	**$22,500**	**-$7,114,100**	**-$7,928,000**
Resiliency benefit	$2,248,900	$2,746,700	$916,200	$2,746,700	$6,633,300
NPV with resiliency	**$2,446,300**	**$2,812,500**	**$938,700**	**-$4,367,400**	**-$1,294,700**

3.3.2 Emissions benefits

The emissions benefits from adding a BESS are significant. The systems would greatly reduce both criteria pollutant and carbon dioxide emissions. Criteria pollutants are directly linked to reduced health issues and generate significant monetary value as a result. Similarly, the monetary value from pricing the adverse environmental impacts of carbon dioxide emissions leads to significant benefits.

Table 19 illustrates the emissions reductions in tons and the resulting monetary benefits. Because the solar PV on the site is included in the base case, the emissions reductions are not reflected in the results. The systems with a large battery show the greatest emissions reduction due to the ability of the BESS to selectively use power from the grid. As climate and health impacts are included in the objective, the system is optimized to use power from the grid at times when grid emissions intensity is lowest. The Phase 2 BESS scenario shows the greatest savings overall, as the larger load amplifies the impacts of the emissions reduction optimization.

Table 19. Emissions reductions and monetary values.

	Phase 1	Phase 2	Phase 1 BESS	Phase 2 BESS
NO_x savings (tons)	0.5	0.5	4.0	11.4
SO_2 savings (tons)	1.4	1.4	14.2	34.1
$PM_{2.5}$ savings (tons)	0.0	0.0	0.3	0.8
Health benefit	**$72,200**	**$73,500**	**$728,400**	**$1,796,700**
CO_2 emission savings (tons)	340	342	3,530	8,785
Carbon reduction benefit	**$19,000**	**$19,000**	**$196,400**	**$488,500**

Table 20 illustrates how adding the monetary value of the reduced air quality health impacts and reduced carbon emissions impacts NPV. By including the value of emissions savings, the Phase 2 BESS scenario achieves a positive NPV

Table 20. Carbon and criteria pollutant monetary value impact on net present value.

	Base case	Phase 1	Phase 2	Phase 1 BESS	Phase 2 BESS
Total cost	$122,200	$208,600	$211,000	$7,503,000	$8,210,400
Energy benefit	$319,600	$274,400	$233,500	$388,900	$282,400
Resiliency benefit	$2,248,900	$2,746,700	$916,200	$2,746,700	$6,633,300
NPV with resiliency	**$2,446,300**	**$2,812,500**	**$938,700**	**-$4,367,400**	**-$1,294,700**
Emissions benefit	$0	$91,200	$92,500	$924,800	$2,285,200
NPV with emissions + resiliency	**$2,446,300**	**$2,903,700**	**$1,031,200**	**-$3,442,600**	**$990,500**

3.4 SENSITIVITY ANALYSES

3.4.1 Integrating the Library Service Center

In addition to the campus at 1600 Emil St and 1501 W Badger Rd, the City of Madison also owns a building about 500 feet east at 1301 W Badger Rd (see satellite image in Figure 7). This building, the Library Service Center, has a 53 kW PV array, a hybrid geothermal HVAC system, and a peak demand of 31 kW. Given the existing PV capacity and proximity to the Engineering and Fleets site, the City of Madison is also considering integrating this facility into the proposed microgrid. Thus, as a sensitivity in our analysis we have also evaluated the impact on costs and benefits of adding this additional load and PV capacity to the site.

Figure 7. The site (red outline) showing the Library Service Center (blue outline) 500 feet east.

A sensitivity with the Library Service Center was run using the full building load during normal operations, with only 10% of power supplied during critical operations (assuming only 10% of the facility load would be considered critical, per the discussion of the VOR123 methodology in Section 2.3.3.2). This adds 53 kW of solar PV capacity and 100,000 kWh per year of load.

Selected results of the analysis with the Library Service Center included are shown in Table 21. The most significant result is for the Phase 1 BESS scenario, where the addition of 53 kW of solar capacity allows for a significant increase in resiliency hours, resulting in a corresponding increase in resiliency benefit. Because the library adds minimal additional load, and even less critical load, the resiliency benefits outweigh the added energy and capital costs (the library requires a minimal increase in the battery capacity).

Table 21. Results summary with the Library Service Center included.

	Phase 1 BESS		*Phase 2 BESS*	
	Base case	**Library**	**Base case**	**Library**
Initial capital cost	$4,197,600	$4,206,000	$4,786,500	$4,799,300
Total cost	$7,503,000	$7,524,900	$8,210,400	$8,237,600
Solar energy exported (kWh)	127,189	140,476	124,654	137,126
Energy benefit	$388,900	$417,900	$282,400	$305,800
Health benefit	$728,400	$758,800	$1,796,700	$1,832,300
CO_2 emission savings (tons)	3500	3682	8800	8943
Carbon reduction benefit	$196,400	$204,900	$488,500	$497,300
Emissions benefit	$924,800	$963,700	$2,285,200	$2,329,600
Resiliency (hours)	1,309	1,726	105	109
Resiliency benefit	$2,746,700	$2,789,000	$6,633,300	$6,675,500
NPV with emissions + resiliency	**-$3,442,600**	**-$3,354,300**	**$990,500**	**$1,073,300**

By integrating the Library Service Center, the additional solar capacity can be used to increase the NPV and resiliency, while the Service Center itself receives the benefit of backup power. During an outage the library would not need to operate at full capacity, but continuous power for the HVAC system would be beneficial as humidity-sensitive library materials are housed in the building.

However, integration would likely be challenging to accomplish due to the distance and the likely need for horizontal drilling to provide an electrical connection. In addition, Library Services currently benefits from MGE’s net metering rate – once integrated with the larger array at the main site, the total would be over the net metering limit, meaning that solar would be reimbursed at the lower wholesale rate, resulting in a net increase in the operating costs for Library Services.

Given these findings, a review of the available solar capacity at the main site is recommended, as an increase in solar capacity of approximately 11% results in a 32% increase in resiliency hours, and 41% increase in overall NPV in the Phase 1 BESS scenario.

3.4.2 Emissions reduction goals

An additional sensitivity was performed on the Phase 1 BESS scenario to understand the impact of increasing emissions reduction targets. The results are shown in Table 22. Note that a reduction beyond 40% was not possible, as REopt did not find an optimal solution for any system with a greater emissions reduction target.

Because the solar capacity cannot be increased, the only way to achieve emissions reduction is to increase the battery size and capacity. The optimization then operates the battery to selectively use energy from the grid; when grid emissions are highest, the battery exports solar to reduce total emissions. When grid emissions are lowest, the microgrid imports energy to serve load and charge the battery. While this causes energy costs to increase, it is more than offset by the emissions benefit. In addition to the emissions benefits, this strategy also results in reduced need for the generator and increased resiliency due to the larger battery.

Table 22. Results summary for Phase 1 scenario with emissions reduction targets.

Emissions reduction target	**None**	**10%**	**20%**	**30%**	**40%**
Battery kW	47	297	594	1,407	3,317
Battery kWh	61	430	1,407	3,146	7,409
Generator kWh	672	445	0	0	0
Solar export (kWh)	269,206	264,100	303,512	372,201	461,465
Initial capital cost	$60,000	$396,600	$1,005,800	$2,310,900	$5,445,100
Total cost	$208,600	$699,100	$1,659,300	$3,633,900	$8,395,600
Total energy benefit	$274,500	$207,500	$69,800	-$122,100	-$500,600
Health benefit	$72,200	$324,500	$557,800	$731,400	$927,900
CO_2 emission savings (tons)	340	2368	4760	7124	9506
Carbon savings	$19,000	$132,000	$264,800	$397,100	$529,600
Emissions benefit	$91,200	$456,500	$822,600	$1,128,500	$1,457,500
Resiliency (hours)	150	159	229	399	1,109
Resiliency benefit	$2,746,700	$2,746,700	$2,746,700	$2,746,700	$2,746,700
NPV with Emissions + Resiliency	**$2,903,800**	**$2,711,600**	**$1,979,800**	**$119,200**	**-$4,692,000**

These results indicate that increasing the battery size will contribute to both emissions reduction goals and resiliency benefits. The reduced reliance on generators means that with a sufficiently sized BESS, it may be possible to eliminate the existing natural gas generator, reducing operating costs, as well as any capital cost that would be associated with integrating the generator into the microgrid.

4 MICROGRID CHECKLIST

Through this feasibility study, we identified best practices for evaluating microgrids for the City of Madison. The following section summarizes these considerations, starting with specific next steps for the site at Badger Rd and Emil St, followed by more general recommendations.

4.1 NEXT STEPS FOR THIS SITE

Electrically interconnect the Streets and Engineering buildings. The most significant assumption included in the analysis is the electrical interconnection of the three existing electrical services at the site. The key first step to allow the site to share loads and resources would be integrating Streets and Engineering. The Streets storage building has no PV currently and a significantly smaller load, so it can be integrated at a later date. Electrical integration, while costly, will allow the site to utilize a single generator and a single BESS, while leveraging the eight planned and existing solar arrays on site. The interconnection will require the services of an electrical contractor, and close coordination with the utility, as a service upgrade will be required.

Specify microgrid-ready inverters for all new PV arrays. While the existing inverters all have SunSpec Modbus capability which would enable them to interface with a microgrid controller, they are grid-tied inverters which require a grid signal to generate power. Specifying multi-mode inverters (which can operate in grid-tied or grid-forming fashion) will ensure that there is sufficient power available to establish a stable signal during islanded operation to support the balance of the inverters. While the BESS inverter will by default be multi-mode, specifying several additional PV inverters as multi-mode in addition can help support the BESS inverter and may lower the total cost.

Consult with vendors to prepare for microgrid integration of existing DER components. While all the PV inverters on site are SunSpec Modbus capable, some may require firmware upgrades or additional hardware to enable integration, and communication cabling may need to be installed. The generator, generator controller, and all associated automatic transfer switches will also require evaluation to determine how they could integrate with a future microgrid controller. The generator currently utilizes an open-transfer switch. In a microgrid configuration, the BESS would utilize a closed-transfer switch to prevent momentary outages during transition to island. Then as the BESS charge drops, the generator would need to come on-line in parallel with the BESS; to accomplish this, the existing generator ATS would likely need to be replaced or upgraded.

Perform a site survey to establish acceptable BESS installation location. The National Fire Protection agency (NFPA) provides guidelines for allowable locations of a BESS, along with required enclosures and fire suppression systems.[28] Given the limited space and high traffic of the site today, identifying a suitable location for a BESS, and confirming the total allowable capacity, will be a critical step before undertaking further microgrid planning.

Consider BESS replacement strategy in the bidding process. The battery cells used in a BESS today naturally degrade over time, a fact which must be accounted for in the design of the system. To ensure that the BESS provides all the expected benefits for the site, there are three typical strategies which the city could consider at installation; replacement, augmentation, and oversizing.[29] The first option is a full replacement roughly 10 years into the project lifetime. With an augmentation strategy, new cells would be added periodically to offset the degradation of older cells, and older cells would be removed as their capacity degrades below acceptable limits. The last option is to oversize the system at the onset, so that as the system degrades, it still hits the minimum capacity needs.

For this site, due to the expected vehicle electrification timeline, a modular augmentation strategy will likely be the most cost-effective; at installation, the BESS should be sized according to the expected near-term EV charging load, with periodic modular expansions corresponding to the expansion of the EV fleet. To accommodate this expected growth, the location where the battery is to be housed should be designed from the outset to be large enough for the final expected battery size.

4.2 GENERAL RECOMMENDATIONS FOR CITY-WIDE PLANNING

Prioritize data collection and start early. The quality and quantity of primary data collected directly impacts the relevance and robustness of the results for the proposed microgrid. Key data to collect should cover the building energy loads (both electric and natural gas). Electric interval data should be collected where available or a robust plan for estimating an hourly load profile and calibrating this to actual usage should be developed. If electrification of vehicles or natural gas-burning heating equipment is planned, determine how to translate the available data (typically annual or monthly) into hourly intervals. To meet the objectives of resilience and financial performance, a microgrid needs to carefully balance loads, sources, and storage elements, all of which fluctuate in real-time. Having robust interval data is vital for determining technology sizes when backup power is a requirement of the microgrid. After completing this exercise for the planned microgrid, it is highly recommended to implement a data collection plan for other critical municipal facilities to aid in future resiliency planning.

For the vehicle fleet, consider implementing a telematics system to record interval data by vehicle type. With a record of the times at which vehicles depart and return to their assigned

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[28] National Fire Protection Association, “NFPA 855: Standard for the Installation of Stationary Energy Storage Systems.”

[29] Shin and Hur, “Optimal Energy Storage Sizing with Battery Augmentation for Renewable-Plus-Storage Power Plants”; EPRI, “Energy Storage, DER, and Microgrid Project Valuation: EPRI DER-VET Analysis in Action.”

facility, along with daily mileage, a more accurate model of the charging load profile could be developed to enhance the BESS sizing optimization.

We also found that there are several intricacies to the required inputs of the tools, including: Financial data points, rebates at the utility, state, and federal level, current utility rate, and potential utility rates. For these reasons, it is important to budget ample time to collect data, review and organize the data, and determine additional inputs.

Consider alternatives for natural gas-burning end uses including generators, space heating, and water heating. In 2020, natural gas usage represented 40% of the utility cost and 81% of the total energy used by the Badger Rd and Emil St site. The majority of this was used for space heating, with some additional use for water heating, the natural gas generator, and the brine heaters. To achieve the city’s emissions reduction goals, nearly all natural gas end uses at this site and other city facilities will need to be converted to electric. This will add significant electric load, requiring larger batteries and PV arrays to meet critical demand at each site where a microgrid is implemented. However, additional electric uses, especially when implemented through a load control system, can also enhance the ability of a microgrid to reduce emissions and increase energy benefits.

Implement smart charging to manage demand, increase self-consumption of solar, and prepare for emergencies. For this analysis, a static EV charging load profile was used based on the assumed charging strategies that would be needed to meet the needs of the fleet. With smart charging, the amount of power used to charge the EV fleet could be modified in real-time based on parameters such as expected time when vehicles will be used again, BESS state-of-charge, and whether the facility is experiencing or anticipating an outage or emergency. With this level of control, the BESS capacity (and thus up-front cost) could be reduced, the benefits could be increased, or some combination of the two.

Consider vehicle-to-grid as a potential solution for powering critical loads from the energy stored in non-critical EVs during outages and emergencies. In addition to smart charging, vehicle to grid (V2G) could be a solution to enable the battery capacity of fleet vehicles to be used in a similar fashion to a standalone BESS. While the infrastructure to implement V2G can be costly, and operation can reduce battery lifespan, there are cases where the benefits outweigh these costs. If V2G can be used to supplement a smaller standalone BESS during outages, the upfront capital cost can be reduced without sacrificing resiliency benefits.

Sites with existing generators should consider lifetime of generator. At sites with existing diesel generators, it is generally not cost effective to replace a generator with battery storage when just looking at resiliency and energy benefits. The diesel generators provide needed resiliency and the upfront costs for batteries is too high for the energy benefits to outweigh the cost. Additionally, if the diesel generator is only running occasionally, the environmental impact can be small.

For these sites, the most financially feasible option for a microgrid installation is likely at the end of the generator's lifetime. At that point, the BESS and its associated benefits can better compete with the generator and provide additional emissions benefits. The site should start by installing solar to lower its emissions and then upgrade to a full microgrid at the end of the diesel generator's lifetime or when emissions reduction at the specific site is deemed critical to meeting city-wide goals.

Adding a BESS to a site with an existing generator may be cost-effective for sites where a large solar PV array is existing or planned. The load shifting and demand limiting benefits of a BESS can be fully utilized at such sites, especially where excess solar generation may otherwise need to be exported to the grid at the lower wholesale rate.

Utilize microgrid ready design during renovations and construction. The upfront capital costs associated with establishing a microgrid are often a deterrent. One solution is to install the microgrid components piece by piece based on their own value proposition, while ensuring they are microgrid ready. For example, solar PV arrays can be installed first, with inverters confirmed to be microgrid compatible. NREL provides suggestions on RFP language to include to ensure solar panels and inverters are microgrid-ready.[30] Language should be included that inverters should comply with applicable provisions in the IEEE Series of Interconnection Standards (specifically IEEE 1547-2018) and that the inverters should be multi-mode DC to AC inverters with islanding functionality.

During renovations or planning, consideration should be given as to how to create or save enough space for the future battery installation.

Consider energy efficiency and demand management to decrease solar and storage capacity needs. When sizing a solar plus storage system, the baseline load is the single most important factor. If there are ways to decrease total energy use through energy efficiency and demand management, this can allow for a smaller and less costly system. As part of an evaluation of the microgrid installation, consider if there are ways to improve efficiency in the building, such as lighting improvements or HVAC system upgrades, or ways to manage demand through plug load or lighting controls.

For sites intended to provide resiliency benefits, it will be important to consider what measures can be installed that can shed or shift load to reduce the amount of energy needed during an outage.

When sizing DER components, determine the critical loads at the facility. The amount of load that must be sustained during an outage is a critical factor in the size of storage required for a microgrid. Consultation with stakeholders familiar with the building and its critical loads is also key to the success of a microgrid.

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[30] Booth, "Microgrid-Ready Solar PV - Planning for Resiliency."

It may also be useful to utilize the Clean Coalition's VOR123 methodology.[31] The methodology suggests that most buildings can split their load into three tiers. Tier 1 represents roughly 10 percent of load and are critical items that require power always. Tier 2 represents roughly 15 percent of total load and are all other priority loads, and Tier 3 represents the last 75 percent and all discretionary loads. To utilize this methodology, split all the major spaces in the building into Tier 1, Tier 2 and Tier 3. From there, data such as square footage, occupancy, or submetering can be used to estimate energy needs for each tier.

Include resiliency benefits in calculations of cost-effectiveness. Resiliency benefits are one of the primary reasons to install a microgrid system and are often significant. It is important to consider the monetary value of these benefits when making decisions about investment. There are several methods a site could use to value resiliency:

- Utilize national estimates from LBNL. This is one of the most cited values of resiliency but is limited as it only includes values for outage durations up to 16 hours[32]
- Estimate the value using NREL's Customer Damage Function Calculator. This tool allows the user to input any damaged equipment costs, lost data costs, food or product spoilage costs, or any other interruption costs[33]
- Estimate human health benefits for a community resiliency center. Other studies have considered their population and estimated how many people would need electricity dependent medical care or heating and cooling centers to estimate health impacts and associated avoided costs[34]

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[31] Lewis and Mullendore, "Valuing Resilience in Solar+Storage Microgrids: A New Critical Load Tiering Approach."
[32] Sullivan, Schellenberg, and Blundell, "Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States."
[33] "Customer Damage Function Calculator."
[34] Rolon, Calven, and Aytjanova, "Solar and Energy Storage for Resiliency."

5 CONCLUSION

A microgrid at the Badger Rd and Emil St site can help meet several City of Madison goals: increase use of renewable energy, improve resiliency, reduce pollution and carbon emissions, and reduce energy costs. The microgrid can help provide these benefits and generate net financial savings over the lifetime of the system. While a complete implementation is costly, there are several lower cost incremental upgrades that the city can implement to enable an eventual microgrid.

The results in this study highlight the various ways that the benefits of a BESS can be evaluated to justify the significant upfront cost, especially as electrification of the vehicle fleet increases the electric load that the microgrid must be able to meet. Important findings include:

Battery sizes and costs increase as the load and emissions reduction goals increase. There are two primary factors that impact battery size – the critical load profile and the site's emissions reduction target. As the electric vehicle fleet expands, the size of the battery increases, which decreases net present value (before emissions and resiliency are accounted for). Similarly, as the emissions reduction target increases, the size of the battery increases. To address this, the City of Madison will need to decide how to value the other benefits that the BESS provides.

The planned PV capacity is not sufficient to support the full critical load after all vehicles are electrified. As modeled, even the largest feasible BESS (10 MWh) could only guarantee backup power for outages of two days or less. There are several ways to address this, the simplest of which would be increasing the solar generating capacity on site. Other strategies such as smart charging and V2G could be used to carefully manage the critical load and increase resiliency.

Including resiliency and emissions benefits significantly increases the net present value compared to having no BESS on-site. The BESS scenarios provide significant resiliency benefits when planning for a major outage on an annual basis. The BESS also provides environmental and health benefits by enabling the facility to selectively utilize power from the grid depending on when the emissions factor is lowest, reducing reliance on fossil fuels and the resulting carbon and criteria pollutant emissions. Across all scenarios, the monetary value of resilience and reduced emissions results in a greatly increased NPV. In the case of the future, fully electrified site (Phase 2) valuing resiliency and emissions changes the NPV from negative $0.7M to positive $1.6M.

Based on these takeaways, we recommend that the City of Madison pursue a microgrid at the site with a BESS. Given that the fleet will be electrified over time, we recommend installing a small modular BESS, with the option to expand over time. This will enable the site to immediately take advantage of the benefits of a microgrid, while enabling staff to study the real-world performance and to make informed decisions about future expansions.

As the fleet electrifies, several tasks should be completed to determine the ideal BESS size:

- Perform a detailed study of usage patterns of vehicles on site to develop a more accurate load profile
- Model expected usage of vehicles during varying types of emergencies to develop a more accurate critical load profile
- Research smart charging solutions that integrate with microgrid controllers to understand options for managing critical charging loads during power outages.

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