Electric Vehicle Charger Placement Optimization in Michigan: Phase III – Distributed Energy Resources

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Michigan Department of Transportation

Auto Companies
- Ford Motor Company
- General Motors
- Toyota

Transmission and Utility Companies

- American Transmission Company
- Cherryland Electric Cooperative
- Consumers Energy
- DTE Energy
- Great Lakes Energy Cooperative
- Indiana Michigan Power
- ITC Transmission Company
- Lansing Board of Water and Light
- Michigan Electric Cooperative Association
- Michigan Municipal Electric Association
- Wolverine Power Cooperative

Charging Station Companies
- ChargePoint
- Greenlots

Electric Vehicle Drivers & Owners

Cities and Communities

- City of Ann Arbor and Ecology Center
- City of Grand Rapids
- City of East Lansing
- City of Marquette
- City of Kalamazoo

Michigan Energy Office
- Robert Jackson

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EXECUTIVE SUMMARY

This report provides a framework to develop policies and infrastructure for supporting plug-in electric vehicles (EV) charging demand and grid integration through distributed energy resources (DER). The developed comprehensive approach is funded and supported by the Michigan Department of Environment, Great Lakes, and Energy (EGLE). Researchers at Michigan State University lead the modeling framework development and execution.

The EV charging demand is predicted to increase the load on the electric grid. Hence, a modeling framework is required to predict the optimum investment technology supporting EV fast-charging demand and reducing the load on the grid. This study estimates the optimum size, type, and location of the DER to support the direct current fast charging (DCFC) demand in 2030. The study captures the existing load on the grid, and the capacity constraints of the grid network, while predicting the optimum investment technology. The potential load from DCFC is derived from the previous study on DCFC station locations for supporting urban trips across Michigan for the year 2030, conducted by the same research team at Michigan State University and supported by EGLE.

This study investigates the characteristics of different DERs (i.e., new battery (NB), second-life battery (SLB), flywheels, solar panels, etc.) to support fast charging. Various battery storage technologies (such as lead-acid batteries, lithium-ion (Li-ion) batteries, sodium metal halide, etc.) are also investigated. The study suggests Li-ion batteries as the optimum storage technology considering the lowest project cost, maximum energy density, and power density. However, the provision of Li-ion SLB and solar panels provides the maximum annual savings in total and electricity costs. Table 1 summarizes the findings for different urban areas for the EV charging demand in the year 2030 (6% market penetration rate) to up to twice the EV demand in 2030.

TABLE 1 Cost savings in major urban areas of Michigan using 4-hour SLB and the solar panels

City	SLB Size (kWh)	Solar Panel Size (sq. meter)	Electricity Savings ($k/yr.)	Total Savings ($k/yr.)
Saginaw	38-900	56-334	95-190	60-110
Muskegon	150-800	56-297	50-100	30-60
Lansing	100-800	37-297	40-85	25-55
Kalamazoo	150-800	56-297	50-100	30-65
Grand Rapids	150-1200	56-446	140-285	80-165
Flint	150-800	56-297	80-160	45-90

It is worth noting that the battery performance and preliminary data are derived from the literature. More in-depth analysis of the battery performance, including experimental analysis, is in progress, and we will update the results as necessary.

This study proposes the location and size of the DER at each of the potential DCFC locations in major urban areas in the state of Michigan. The study also provides the investment cost and savings with DER deployment at the DCFC locations. The main findings of the study are as follows:

1. Providing the maximum size of the solar panels considering site restrictions is the optimal solution as it provides substantial overall and electricity savings.
2. Even though the life of SLBs is smaller than the NB, the SLB provides more significant savings as compared to NB due to lower investment costs.
3. Both solar panels and SLBs should be provided for maximum savings. These savings can be further increased if more area is available for solar panels and the SLBs.
4. The proposed charge/discharge schedule of SLB should be adopted for maximum savings. The pattern ensures that the SLB charges during the off-peak hour or when the electricity prices are low stores the intermittent solar energy, and discharge during the peak hours.
5. The 4-hour storage duration SLB is the optimum solution compared to 2-hour SLB or 6-hour SLB because the 4-hour SLB is cheaper than the 2-hour SLB, but it is fast enough (as compared to 6-hour SLB) to support the demand during peak hours.
6. Upgrades of grid components (i.e., feeder line, substation, segment, etc.) might be required along with the SLBs and solar panels. The investment cost of grid upgrades depends upon the capacity constraints of the grid, existing load, and the EV demand at the particular location.

The developed optimization framework predicts the size and location of DER in major urban areas of Michigan, listed as Saginaw, Lansing, Grand Rapids, Muskegon, Flint, and Kalamazoo. The models developed in this study can be implemented in other cities based on the data availability.

INTRODUCTION

The electric vehicles (EV) adoption has increased rapidly in recent years. Electric car sales increased by 40% in 2019 compared to the previous year (IEA, 2020). The rapid growth of the EV market requires the development of proper electric vehicle charging infrastructure to serve the electric energy demand (Ma, 2019; Negarestani et al., 2016). While the level 1 and level 2 chargers are typically used for overnight charging at home supporting intracity trips (Negarestani et al., 2016), the level 3 direct current fast charging (DCFC) is used for public applications similar to gasoline service stations (Morrow et al., 2008; Yilmaz and Krein, 2013). The deployment of DCFC chargers is mandatory for the widespread adoption of EVs (Chakraborty et al., 2019). Many EV users might not have access to home chargers or chargers at the workplace, with an increase in the market share of EVs (Ghamami et al., 2020). The high adoption rate of EVs requires deploying a DCFC network to support urban trips of the EV users (Ghamami et al., 2020).

However, the widespread network of DCFC stations will impose an unpredictably large load on the electric grid (Gallinaro, 2020; Knupfer et al., 2018; Richard and Petit, 2018a). The extra load on the grid would require upgrading the electric grid network, which can be very expensive. In light of the above, the provision of distributed energy resources (DER) can support the fast charging demand of EVs and mitigate the electric grid upgrade cost. Thus, there is an increasing need for the DER to support the rising charging demand for EV trips.

The Michigan Department of Environment, Great Lakes, and Energy (EGLE) initiated the investment in an analytical approach to find the optimum investment technology supporting the DCFC demand and reducing the load on the grid. This study develops a modeling framework to find the optimum size and location of DER to support the DCFC demand. The study considers the fast charging demand of urban trips of EV users, existing electricity demand (other than EV demand), electric grid network, and cost associated with building DER to find the optimum investment strategy.

The analytical approach includes a mathematical model that requires input data from different stakeholders to estimate the optimal investment technology for DER at the DCFC locations. The data was collected through a series of stakeholder meetings facilitated by EGLE. The stakeholders involved are utility companies, cooperatives, municipalities, charging station companies, Metropolitan Planning Organizations, communities, the automotive industry, and the State of Michigan departments. The study developed an analytical framework that incorporates the EV charging demand obtained through simulated trips of EV drivers and optimum charging infrastructure locations from phase II of the charger placement project. The existing electricity demand, grid connections, and constraints are the other inputs to the modeling framework. The time-dependent energy storage and solar panel power generation models are embedded in the optimization framework to estimate the optimum investment strategy.

The Problem Statement is explained in the next section of the report, followed by a review of the relevant studies. Then the next section describes the methodology, followed by data collection. Finally, the results for each of the urban areas and the report's conclusion are presented.

PROBLEM STATEMENT

The increasing market penetration rate of electric vehicles requires a network of DCFC stations. The network of DCFC chargers will reduce the charging time and ease concerns related to the limited driving range of EVs. However, fast-charging stations will increase the load on the electric grid network, causing supply-demand imbalances and degradation of the electric grid system. The electric grid transmission and distribution system, including transmission lines, substations, feeder lines, segments, etc., might need to be upgraded to support the rising EV charging demand. The investment cost to upgrade various grid components can be substantial depending upon the location of DCFC stations and the arrival rate of EVs. However, the DER, such as energy storage systems (ESS), solar panels, etc., can support the EV charging demand, reduce the load on the electric grid, and reduce the electricity cost. This study aims to estimate the optimum investment technology to support the rising EV charging demand while minimizing the system cost. The system cost includes the investment cost of DER (i.e., ESS, solar panels), electric grid upgrade cost, and electricity cost. The study investigates the critical locations that would require the provision of DER, which depends upon the EV charging demand, existing electricity demand, the capacity constraints of the electric grid network, and the rate of electricity. This study seeks to answer the following questions:

- What would be the best type of DER (i.e., batteries, flywheels, solar panels) to support the EV fast-charging demand in urban areas of Michigan?

- What are the optimum locations for DER to support the DCFC network and reduce the load on the grid?

- What is the optimum size and investment required for each urban area?

- What would be the overall savings (including electricity cost savings) for each urban area?

LITERATURE REVIEW

The widespread usage and rise in the EV charging demand will affect the electric grid (Negarestani et al., 2016; Rafi and Bauman, 2021). The EV charging stations can affect the electric grid stability and overload the distribution system (Khalid et al., 2019). The distribution system might have to be reinforced to support EV charging demand during peak periods (Pieltain Fernandez et al., 2011). Further, the DCFC stations will impose an unpredictably large load on the electric grid (Gallinaro, 2020; Knupfer et al., 2018; Richard and Petit, 2018a). The increase in demand can be as high as 1.2 MW, with a typical Electrify America installation of two 350 kW chargers and four 150 kW chargers along the highways (Nicholas and Hall, 2018). The increasing demand and the associated power may require grid upgrades and costly transformers (Nicholas and Hall, 2018). A well-planned investment in DER technology is crucial to support the rising demand for EVs, ensure grid stability, and reduce the grid upgrade cost.

Many studies have considered DER, such as solar panels and ESS, including battery and flywheels, to support DCFC stations. One of the studies shows that the battery energy storage system can provide up to $157,000 of savings annually for six 350 kW chargers at a DCFC station (Francfort et al., 2017). Energy loss, charging demand, and life cycle costs of ESS, are also critical factors influencing the optimum size of ESS supporting fast-charging stations (Negarestani et al., 2016). Cost-benefit analysis is another method for minimizing the operating cost of DCFC stations considering connection costs, installation costs, and ESS life cycle costs (Gjelaj et al., 2017c). The studies have assessed the integration of bidirectional DCFC with ESS (Gjelaj et al., 2017a) and use of ESS to ameliorate the impacts on the electric grid (Gjelaj et al., 2017b). The ESS degradation, trade-offs between the power rating of DCFC station, and size of the ESS have been studied recently (Richard and Petit, 2018b). Another study compared second life batteries (SLB) with new batteries (NB) of lithium-ion (Li-ion) to support EV fast-charging demand and reduce the electric grid load (Kamath et al., 2020). The study concluded that the levelized cost of electricity reduces by 12-41% when using SLB instead of new batteries. A comparison of different storage technologies proposed flywheel storage systems to minimize the energy cost and storage cost at the fast charging station (Negarestani et al., 2016). However, the study did not consider the cost of upgrading the grid and the self-discharging losses in the flywheel. It is worth noting that technological advancements have changed the cost of different ESS (especially the Li-ion batteries).

Renewable energy sources can assist with peak-shaving and reduce electric grid power losses (Ma, 2019). Further, the provision of ESS can improve or altogether remove the power fluctuations of renewable sources power generators (Ma, 2019). Studies have estimated the impact of variation in the number of DCFC stations, load profiles, electricity price, and geographic locations on the economics and energy performance of DCFC stations with solar panels and ESS (Yang and Ribberink, 2019). The system provides energy savings, and the economic viability is promising, considering the changes in the unit price of DER between 2021 and 2026, with a payback period of 12-16 years (Yang and Ribberink, 2019). Studies consider the annual cost of energy to estimate the location and size of level 2 charging stations, distributed ESS, and solar panels/wind turbines (Kandil et al., 2018). The cost includes the investment cost of technologies, energy consumption, and renewable energy savings. The study suggested that to support existing EV demand; the solar panels can provide savings of around 70-75% as opposed to distributed ESS, which can provide only about 15-20% savings. Li et al., 2019 developed an optimization framework to minimize the electricity cost and the number of charge/discharge cycles of ESS for the solar panel assisted EV charging station (Li et al., 2019). The study showed that optimum coordination between the energy resources and EVs could maintain stable power system operations and reduce the charging cost. Another study proposed a solar panel and lithium ferro phosphate battery as the optimal solution out of three ESSs, including lead-acid and lithium nickel cobalt aluminum oxide batteries (Nizam and Wicaksono, 2019). The optimization minimizes the capital and operating cost of the off-grid charging station in rural areas (Nizam and Wicaksono, 2019). Ugirumurera and Haas, 2017 estimated the optimum number of solar panels and size of ESS to support the EV charging system with energy generation exclusively by the solar farm. The optimum number of solar panels decreases with an increase in the average delay of EV users and the power rating of each charging station (Ugirumurera and Haas, 2017). One of the studies implemented GA and Monte-Carlo methods to optimize the location and capacity of solar panels and ESS to support charging stations considering uncertainties in EV demand, solar panel power, and electricity price (Khanghah et al., 2017). The study showed that the ESS and solar panels could reduce the operating cost, power losses, and voltage sags in the system. Hilton et al., 2019 developed an optimization framework to maximize the profit and minimize the electric grid connection cost and associated energy cost for a solar panel-ESS charging station (Hilton et al., 2019). The study showed that the solar farm and ESS reduce grid energy use and provide savings, especially if the grid connection cost is high.

The current studies showed that the ESS and solar panels effectively support the EV charging demand, reduce the power demand from the grid, and provide overall savings. However, none of the studies have considered the entire electric grid distribution and transmission system (transmission line, feeder line, substations, etc.) constraints and compared the upgrading cost of the grid network to that of investing in DER. In addition, there has been limited research on the comparison of different ESS (NB, SLB, flywheels, etc.) to support DCFC stations. Further, most studies focused on providing solar panels over the electric distribution network with a potentially large area available for its deployment. However, such a large area might not be practically available, and the charging stations might not have enough space to provide such a huge solar farm. This study aims to estimate the optimal investment technology (DER, grid upgrades) with the minimum cost to support the EV charging demand at the DCFC network. This network of DCFC stations along with the increased electric miles traveled, will increase the electricity demand and affect the electric grid stability and degradation of the electric grid distribution system. The study considers the investment cost of different DER (NB, SLB, flywheels, etc.), grid upgrade, and connection cost, and the operations of DER and energy cost from the grid. The study develops a modeling framework to consider the capacity constraints of the electric grid network, the spatiotemporal EV charging demand, the existing spatiotemporal load on the electric grid, and different types of DER to find the optimal investment technology at the DCFC stations.

METHODOLOGY

The methodology includes developing an optimization model and solution approach using commercial solvers (i.e., CPLEX). The input data consists of the DCFC stations network (current and potential), spatio-temporal distribution of EVs' electricity demand, existing electricity demand (excluding EV demand) in the electric grid network supporting the DCFC station network, electric grid connections, capacity constraints, cost of upgrades, and the characteristics of different DER (i.e., cost, performance, charging and depletion rate). The framework considers the entire electric grid network and its components (transmission line, substations, feeder line, segment, sub-segment). A schematic description of the electric grid network with existing demand, potential EV demand, and DER is presented in **Figure 1**. The input data is fed into the optimization model to estimate the optimum investment technology with maximum cost savings.

The inputs and the outputs of the model are listed below:

Inputs

1. Demand distribution over entire electric grid network
   a. Spatiotemporal EV charging demand
   b. Spatiotemporal existing electricity demand
2. Electric grid network details of segment/subsegment, feeder line, substation, transmission line
   a. Spatial capacity
   b. Cost of upgrading
   c. Connections and locations
   d. Spatiotemporal time-of-use (TOU) electricity rate
   e. Life of the grid components
3. Distributed energy resources (Li-ion NB BESS, Li-ion SLB BESS, FESS, solar panels)
   a. Performance and charging/discharging rate
   b. Unit cost of investment (includes installation, balance of plant, inverters, etc.)
   c. Life

Outputs

1. Distributed Energy Resources (Li-ion NB BESS, Li-ion SLB BESS, FESS, solar panels)
   a. Size
   b. Location
   c. Time dependent charge/discharge profile and power output
2. Electric grid network
   a. Additional capacity requirement of upgrading subsegment, feeder line, substation, transmission line
3. Investment cost & savings

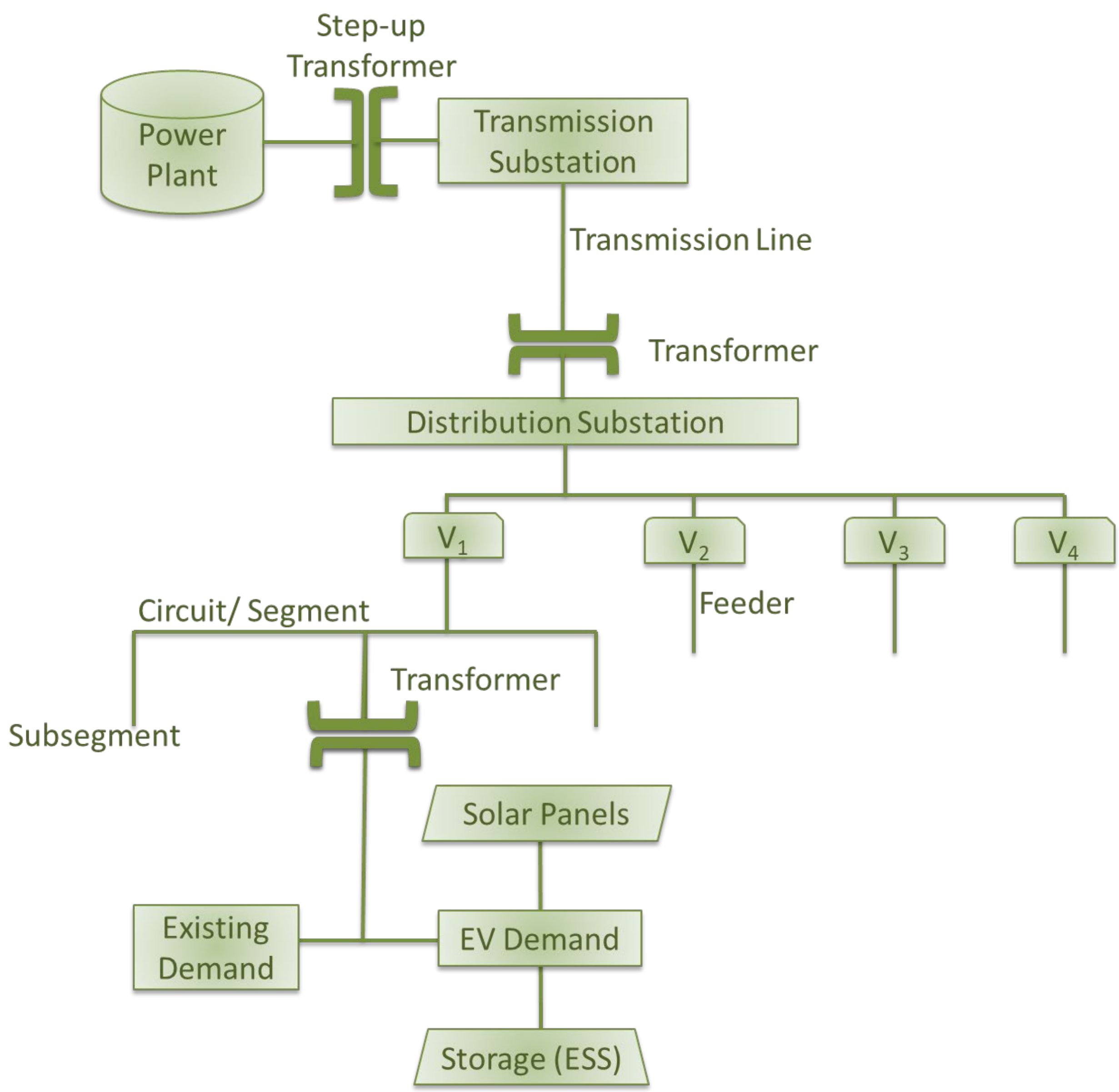


Figure 1 A schematic description of electric grid network

Optimization model

The optimization model is developed to minimize the system cost, including the cost of upgrading grid components (i.e., transmission line, substations, feeder line, segment, sub-segment), investment cost in DER (i.e., Battery ESS (BESS), Flywheel ESS (FESS), and solar panels), and the total cost of energy to refuel EVs. The output of the model is the capacity or size of ESS, area of the solar panels, and potential upgrades of the electric grid components (if any) to support the EV demand, reduce the load on the grid, and the cost of electricity. Note that the focus of the study is to estimate the type and size of DER at the DCFC stations. The objective function of the proposed model is defined below. Further, the parameters used in the model are defined in **Table 2**.

$$\min \begin{cases} \sum_{i \in I} \left(\beta^i \frac{CB \times BS^i}{Z} + (1-\beta^i) \frac{CK \times FS^i + CL \times \Psi^i}{Q} \right) + \sum_{i \in I} \frac{CI \times \rho^i A^i}{Y} + \\ \left(\sum_i \frac{CG \times AG^i}{X} + \sum_{j \in J} \frac{CF \times AF^j}{V} + \sum_{k \in K} \frac{CS \times AS^k}{U} + \sum_{l \in L} \frac{CT \times AT^l}{H} \right) + \\ \sum_{i \in I} \sum_m \mu^m \sum_{t \in \Gamma} \left(EL_t^{im} (\alpha_t^{im} R_t^m + (1-\alpha_t^{im}) O_t^m) + FR^i \right) \end{cases} \quad (1)$$

Table 2 Description of different parameters used in the model

Variable	Definition
BS^i	Size of battery ESS at DCFC location i (kWh)
FS^i	Size of flywheel ESS at DCFC location i (kWh)
Ψ^i	Maximum power of proposed flywheel (kW)
AG^i	Additional subsegment/segment capacity (kW)
AF^j	Additional feeder line capacity (kW)
AS^k	Additional substation capacity (kW)
AT^l	Additional transmission capacity (kW)
A^i	Area of the solar panel at DCFC location i (sq.m)
EL_t^{im}	Net energy required/available from/to the electric grid by the ECS (kWh)
α_t^{im}	Binary variable indicating if the energy is inflow (1) or outflow(0)
CB	Unit project cost of BESS ($/kWh)
CK	Unit energy project cost of FESS ($/kWh)
CL	Unit power project cost for FESS ($/kW)
CI	Unit project cost of the solar panel ($/kW)
CG	Unit cost of subsegment/segment ($/kW)
CF	Unit cost of the feeder line ($/kW)
CS	Unit cost of substation ($/kW)
CT	Unit cost of transmission line ($/kW)
H	Life of the transmission line (years)
U	Life of substation (years)
V	Life of feeder line (years)
X	Life of segment (years)
Y	Life of solar panel (years)
Q	Life of flywheel (years)

Z	Life of battery (years)
R_t^m	Electricity rate (\$/kWh) at time t in the season m
O_t^m	Outflow rate (\$/kWh) at time t in the season m
FR^i	Fixed electricity rate for the base electricity provision cost (\$/day)
β^i	Binary variable indicating if the battery (1) or the flywheel (0) is selected
μ^m	Length of the season m (summer or winter) (days)
ρ^i	The efficiency of the solar panel at location i (0-1)

The objective function has three main components. The first component is the investment cost of DER, which includes the project cost for BESS (NB/SLB), FESS, and solar panels. It is worth noting that the project cost includes the cost of ESS (battery packs, flywheels, etc.), the balance of plant, inverter cost, construction cost, cost and racking of solar panels, electrical balance of system, installation cost, etc. The cost is a function of the size of DER at different locations, the average life of the DER, and the unit cost of DER. The second term is the cost of upgrading the grid components (i.e., transmission line, substation, feeder line, segment) which depends on the additional capacity required to support EV demand, the life of grid components, and the unit cost of grid components. The third term is the cost of electricity to refuel EVs, which depends upon the net energy required from the grid and the TOU of electricity rates. This study also considers credits for sending the excess energy back to the electric grid. Further, the objective function is defined as minimizing the normalized ownership cost (\$/year) considering the life of different DER, grid components, and the annual cost of purchasing electricity. The result would be the optimum investment technology that provides maximum cost savings and ensures grid reliability while serving the EV demand at different DCFC locations.

The objective function of the study is followed by different constraints that track the energy flow through the DER and grid components and ensure that this energy flow does not exceed the capacity of these components at any time instance. These constraints are defined by a series of models, such as the supply-demand model, energy storage charging/discharging model, and solar panel power generation model, described in the following subsections.

Supply-demand model

To ensure the feasibility of charging at each DCFC station, the available supply of energy at any time should be greater than the demand. The demand required includes EV charging, current electricity usage, and the power to charge the ESS. The available energy resources are the electric grid network and solar panels. ESS can be an energy source primarily used based on TOU electricity rates. Further, the capacity of each grid component (i.e., transmission line, substation, feeder line, and segment) should be greater than the demand. Hence, a time-dependent supply-demand energy model is developed to ensure that the capacity of the grid components and total power/supply generated at any instant of time is greater than the EV energy demand and the existing electricity demand. The model also captures the seasonal variation in the current demand. However, the EV demand is assumed to be fixed throughout the entire season as it is the demand generated through urban trips, mostly commute trips.

Energy storage model

The energy stored in the ESS (BESS and FESS) at the end of any time is a function of charging/discharging power, self-discharge losses, and the energy at the previous time interval. The charging/ discharging power further depends on the power capacity of the ESS. The energy stored in the ESS should remain within the capacity boundaries of the ESS. Further, the battery ESS is not allowed to discharge below 20% of the battery capacity, thereby reducing the depth of discharge and protecting the battery's health. The time-dependent energy storage model tracks the energy flow through ESS and provides information about the charge and discharge patterns throughout the day.

Solar Panel Power Generation Model

The power generated by solar panels at any instant of time depends upon the solar radiation intensity, the efficiency of the solar panel, and the area of the solar panel. The solar radiation intensity is a function of the cloud coverage and the sun elevation angle (Ehnberg and Bollen, 2005; Nielsen et al., 1981; Ugirumurera and Haas, 2017). These parameters affect the solar panel power output throughout the day and the season. Hence, a time-dependent solar panel power generation model is considered, which tracks the solar power output at any instant, considering variation in these parameters throughout the entire season.

DATA COLLECTION

The input data includes the proposed and current EV fast charging (DCFC) station network, EVs energy demand, existing energy demand (other than EV demand), electric grid network details and capacity constraints, ESS types and characteristics, and solar panel characteristics and weather conditions. The details of obtaining each of these data sets are explained in this section.

DCFC locations and EV energy demand

The potential DCFC locations in Michigan are obtained from Phase-II of the "Electric Vehicle Charger Placement Optimization in Michigan" by our research team (Ghamami et al., 2020) (Figure 2). These locations were estimated based on the simulated urban trips of EV users throughout the road network of different urban areas in Michigan, corresponding to the proposed

EV market penetration rate (6%) in the year 2030 (Ghamami et al., 2020; Kavianipour et al., 2021). Similarly, the time-dependent EV energy demand and power demand at these DCFC locations are extracted based on the travel patterns. Note that the battery sizes of all EVs are assumed to be 70 kWh (recommended by car companies), and the charging power of DCFC chargers is assumed to be 50 kW (based on the current charger installation approaches in the state of Michigan).

Existing energy demand and electric grid network details

The existing energy demand, grid network details, and capacity constraints are obtained from utility companies, cooperatives, and municipalities. The companies provided data for the electric grid network and connections (i.e., substation, feeder line, segment, etc.) that will serve the proposed DCFC locations, existing energy demand, upgrade costs, and capacity constraints of the electric grid network. It is worth noting that the data was not available for some potential DCFC locations; thus, these locations are not considered for the analysis. A total of 75 DCFC locations within the major urban areas of Michigan were considered (i.e., Saginaw, Lansing, Flint, Grand Rapids, Kalamazoo, and Muskegon). The locations are presented below.

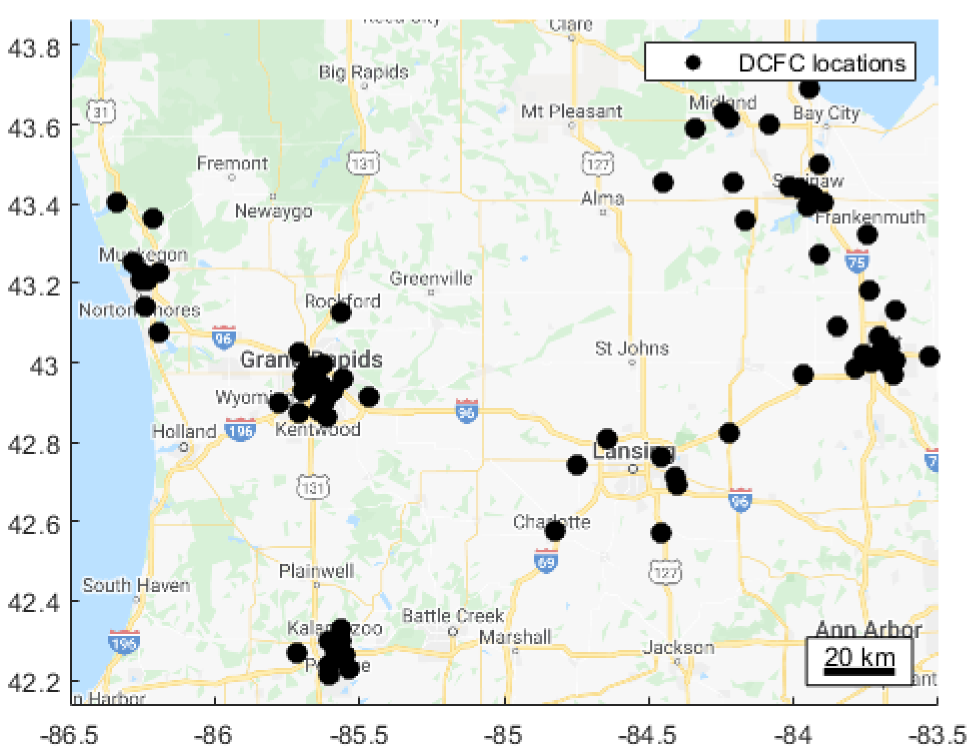


Figure 2 The proposed DCFC stations in Michigan in 2030, considered for DER analysis (Ghamami et al., 2020; Kavianipour et al., 2021)

Energy storage systems types and characteristics

The study considered different types of ESS technologies which include Li-ion battery, lead-acid, redox flow battery, sodium-sulfur, sodium metal halide, zinc-hybride cathode, sodium-ion battery, flywheels (Beacon Power, 2021; Kane, 2021; Mongird et al., 2019; Patel, 2021; Rafi and Bauman, 2021). The Li-ion batteries are deployed across various industries due to their high power density, high energy density, and performance (Mongird et al., 2019). The price of ESS technology is consistently reducing due to significant demand in the EV industry (Mongird et al., 2019). These batteries are used in residential and commercial buildings, distribution grids, renewable generation smoothing, etc. (EASE, 2022). Lead-acid batteries are also used for various applications such as load following and time-shifting, but these are not used for small portable systems (Mongird et al., 2019). Redox flow batteries consist of electrolyte solutions in tanks acting as cathode and anode (Mongird et al., 2019). The electrolyte is passed through a membrane to generate and store energy. Redox flow technology is currently in the early phase of commercialization, but it is expected to provide long life, easy scalability, and efficient operation at low temperatures(Mongird et al., 2019). Further, due to low energy density, large storage tanks are required (EASE, 2022). Redox flow batteries are mainly utilized for peak shaving and energy time-shifting (EASE, 2022). Sodium-sulfur battery is another electrochemical energy storage system that has high energy density but it is highly corrosive, requires high operating temperatures ($\boldsymbol{300 - 350^0 C}$), and consequent safety requirements (EASE, 2022; Mongird et al., 2019). Sodium metal halide (sodium nickel chloride) is used for various application such as residential buildings, EVs, renewable generation smoothing, etc (Mongird et al., 2019). These batteries have smaller range than other electrochemical storage, but have high performance, durability, and low sensitivity to ambient temperature (EASE, 2022; Mongird et al., 2019). Zinc-hybrid cathode batteries utilize widely available materials and can be supplied at a low cost (Mongird et al., 2019). The sodium-ion batteries are in the development phase and are expected to replace Li-ion in the following years (especially in storage applications) as the cost of sodium is very low and available in abundance (EASE, 2022). Further, this technology is safer, operates at lower temperatures, provides faster charging, and has higher cycle life efficiency as compared to Li-ion batteries (Kane, 2021; Patel, 2021). However, the energy density of these batteries is currently lower than Li-ion batteries (Kane, 2021). Flywheels store energy in the form of electromechanical energy (Mongird et al., 2019). It consists of rotating cylinders that store energy in the form of kinetic energy. The electric energy is withdrawn by slowing down the rotating cylinder. The flywheels have longer life cycles and fast response time, making them suitable for frequency regulations and renewable smoothing (Mongird et al., 2019). The data related to different types of ESS, their characteristics, and their feasibility to serve at the DCFC locations is obtained from various studies in the literature (Beacon

Power, 2021; Cole et al., 2021; Kane, 2021; Mongird et al., 2019; Patel, 2021; Rafi and Bauman, 2021). The following table represents the characteristics and project costs of different ESS:

Table 3. Different types of energy storage technologies (Beacon Power, 2021; EASE, 2022; Kane, 2021; Mongird et al., 2019; Patel, 2021; Rafi and Bauman, 2021)

ESS Type	Project Cost* ($/kWh)	Life (years)	Energy Density (Wh/L)	Power Density** (W/L)
Sodium- Sulfur	669	13.5	40	10
Li-Ion	362	10	90-130	23-33
Lead Acid	464	3	16	4
Sodium Metal Halide	669	12.5	65	16
Zinc-Hybrid Cathode	433	10	17	4
Redox Flow Battery	650	15	13	3
Flywheel	10,124	20	18	74
Sodium-ion (Current projection)	<Li-ion	>Li-ion	<Li-ion	>Li-ion

*The cost includes capital cost, power conversion system, the balance of plant, and construction cost
**Assuming energy/power=4 for batteries and 0.25 for flywheel

It can be observed that the Li-ion battery has the lowest project cost. Further, among the different battery technology, Li-ion batteries have the maximum energy density and power density. Thus, the Li-ion is the optimum choice among the batteries and is considered for analysis. The study also considers flywheels for the analysis due to the significantly high-power density and their applicability during the peak power demand of EVs.

The study also considers SLB Li-ion batteries. The batteries are remanufactured after their end of life (EOL) to be used as SLB. The cost of remanufacturing SLB is around 30% of NB (Neubauer et al., 2012). The comparison of SLB with that of the NB Li-ion battery is as shown below:

Table 4 Comparison of second-life batteries versus new lithium-ion battery

	NB Li-ion battery	**SLB Li-ion battery**
Battery pack Cost	$137/kWh (BloombergNEF, 2020)	30% of new battery (Neubauer et al., 2012)

Battery Life	10 years (Kamath et al., 2020)	3-7 years (Kamath et al., 2020)
Battery Energy Capacity	Depends on the Size	70-80% of a new battery (Kamath et al., 2020)

The study also considered BESS with different storage durations. The storage duration is the time to charge/discharge the full battery at its power capacity. The smaller storage duration would mean that the battery can charge/discharge faster, which might be required, especially during peak hours. However, batteries with smaller storage durations are more expensive. The projected capital cost for different storage durations is as follows (Cole et al., 2021):

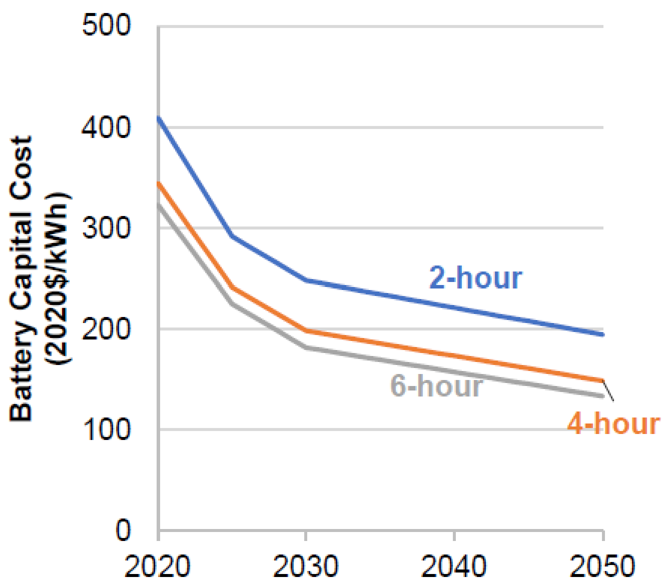


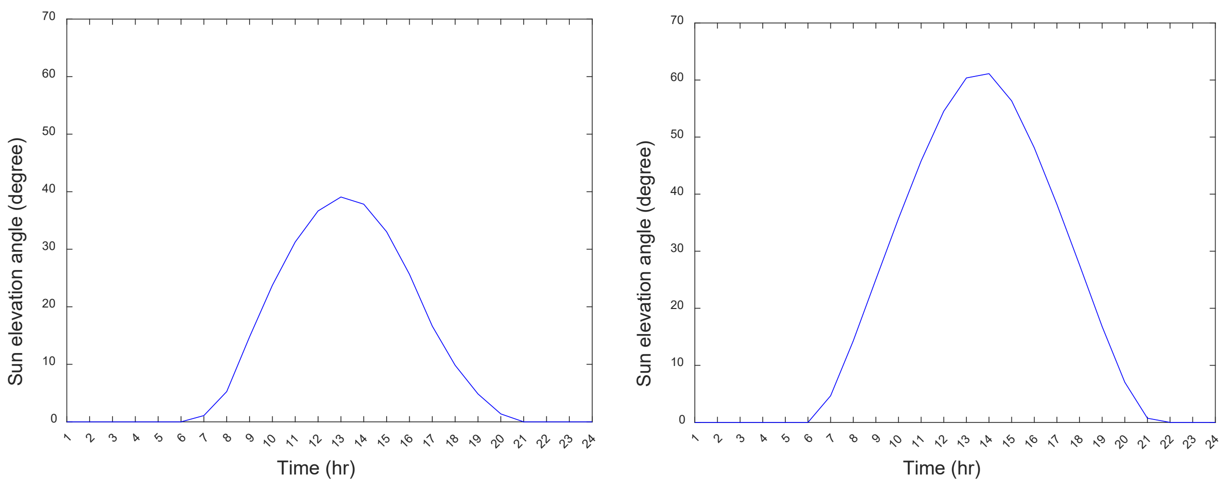
Figure 3 Projected BESS unit project cost with different storage durations (Cole et al., 2021)

This study considers the projected cost of the BESS system in 2050, including battery pack, balance of plant, inverter, construction cost, etc. Finally, the battery size is limited to 50 kWh per 50 kW charger due to area restrictions depending on site conditions (Gjelaj et al., 2020).

It is worth noting that the battery performance and preliminary data are derived from the literature. More in-depth battery performance analysis, including experimental analysis, is in progress as a separate project and will update the results as necessary.

Solar panel characteristics and input data

The solar panels' output power depends upon the efficiency of the solar panels, sun elevation angle, and cloud coverage. The sun elevation angle throughout the year at different locations in Michigan is obtained from SunEarthTools, 2021. The sun elevation angle for the city of Saginaw, during winter (October-May) and summer season (June-September) is shown in **Figure 4**. Note that these figures represent the sun elevation angle averaged over all the days in the given season (winter or summer). The cloud coverage data throughout the year is obtained from Weather Spark, 2022 (**Figure 5)** Note that the variation in sun elevation angle and cloud coverage is found to be similar in all urban areas of the Michigan. Hence, same variation is assumed for all the areas in Michigan. Finally, the solar panel efficiency of 19.5% (Feldman et al., 2021) and cost of \$0.68/W (NREL, 2021) are considered in this study. . The cost of the solar panels is the entire project cost, including inverters, structural balance of system (racking), electrical balance of system, installation cost, etc. The projected cost for the solar panels is considered to be for the year 2050 (NREL, 2021). It is important to note that the area of the solar panels is restricted to the maximum area based on the site conditions at each of the charging stations. Thus, the solar panel area is restricted to the charging/parking spot area per charger (Schmitt, 2016).



a) Winter season b) Summer season

Figure 4 Variation in sun elevation angle during the a) winter and b) summer season in Saginaw, Michigan (SunEarthTools, 2021)

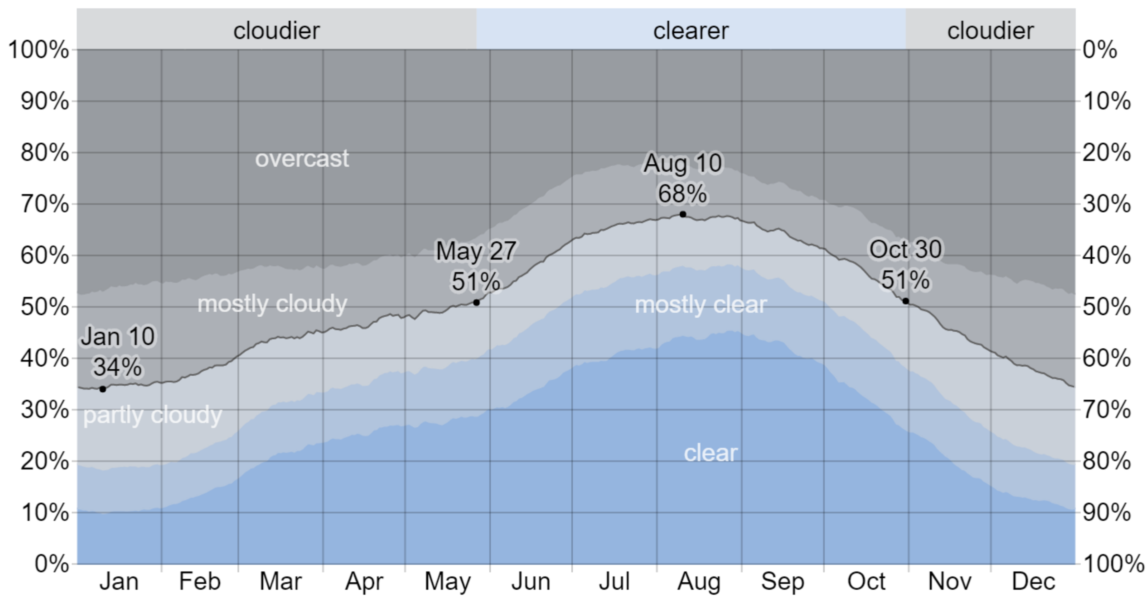


Figure 5 Variation in cloud coverage over the entire year in Saginaw, Michigan © WeatherSpark.com (Weather Spark, 2022)

RESULTS

The model is implemented to obtain the optimum size of DER, required grid upgrades, infrastructure cost, and savings. The study considers different scenarios which includes different combinations of DER (i.e., Li-ion NB ESS, Li-ion SLB ESS, FESS, solar panels), variation in EV charging demand, different storage duration of batteries, projected cost of the DER. These scenarios are listed as below:

- DERs
  - BESS, FESS, and solar panels
  - BESS, FESS only
- Battery cost, type, and storage duration
  - 2-hour storage duration
    - Li-ion NB $190/kWh
    - Li-ion SLB $145/kWh
  - 4-hour storage duration
    - Li-ion NB $150/kWh
    - Li-ion SLB $115/kWh
  - 6-hour storage duration
    - Li-ion NB $140/kWh
    - Li-ion SLB $105/kWh
- EV load factor (EV demand)

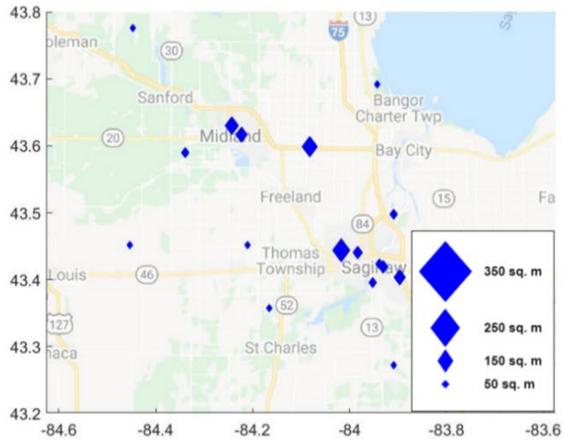
- EV demand in the year 2030
- 1.5 times the EV demand in the year 2030
- 2 times the EV demand in the year 2030

The results are obtained for the 75 DCFC locations in the six major urban areas (i.e., Saginaw, Lansing, Flint, Grand Rapids, Kalamazoo, and Muskegon) of Michigan. The analysis has been done for the 2030 EV demand, 1.5 times the EV demand of 2030 (EV load factor of 1.5 means demand equivalent to 1.5 times the demand in the year 2030), and 2 times the EV demand of 2030, to predict future requirements of EV charging.

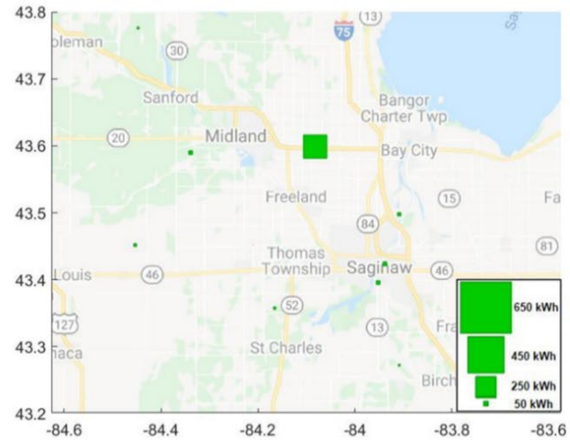
The suggested size of the battery (kWh) and the solar panels (square meter) for the various urban areas for a 4-hour storage duration (Li-ion NB and SLB) are presented in **Figures 6 to 17.** Further, analysis results for different storage durations (2-hour and 6-hour) for Li-ion NB and SLB are presented in appendix A (**Figures 20 to 43**). The suggested optimum approach is the provision of solar panels at all the locations in all the cities. The size of these solar panels is the maximum area that can be provided depending upon the site area restrictions at each particular location. These solar panels provide savings in the electricity cost, charge the battery (especially during the summer and highest sun elevation angle), and supply extra energy to the electric grid (if any). The size of the battery depends upon the type and cost of the battery (NB versus SLB), the cost of upgrading the grid, and the EV load factor. When considering the NBs, BESS is not the suggested optimal solution for many locations state-wide due to the high investment cost for the battery as compared to the cost of upgrading the grid. However, with SLBs, it is suggested to provide batteries at all the locations, and the required size of these batteries is much larger than that of NBs. The investment cost for SLB is lower than upgrading the grid. Further, these batteries efficiently utilize the TOU electricity rates by charging during off-peak hours and discharging during peak hours. Note that the cost of grid upgrades depends upon the capacity constraints of grid components at a given location. Note that flywheels are not the optimal solution as these have higher investment costs than batteries.

The temporal variation of demand in summer for an EV load factor of 2 at one of the locations in Saginaw, Michigan, is shown in **Figure 18** (at the Grid level) and **Figure 19** (at DCFC station level). **Figure 18** shows that the feeder capacity is less than the peak hour demand (existing demand plus EV demand). Solar panels and batteries are provided to support the extra demand and reduce the load on the grid. **Figures 18a** and **18b** display the load profile for NB and SLB, respectively. **Figure 19** represents the detailed temporal demand/supply at DCFC level for batteries, solar panel output, and EV energy demand, considering the TOU electricity rate. The SLB (**Figure 19b)** can utilize the TOU electricity rate more efficiently than the NB (**Figure 19a)**. The SLB has a larger size and can store more energy than NB. It is evident from the figures (especially **Figure 19b)** that the battery charges from midnight to morning when the electricity price and demand are low. The battery discharges during the morning peak hour when the electricity price is higher. However, it again charges around noon when the solar power output is maximum. Finally, the battery again discharges during the evening peak hour with the high TOU electricity rate.

The total cost breakdown for the different cities considering SLBs and solar panels for a 4-hour storage duration is shown in **Table 5.** It can be observed that the provision of DER provides substantial savings in the annual electricity cost ($40,000-$285,000) and the annual total cost ($25,000-$165,000) for each of the major urban areas in Michigan. The maximum savings are in Grand Rapids, Michigan and the minimum savings are in Lansing, Michigan. The total savings are smaller because it includes additional investment costs for DER. Table 6 shows the same cost breakdown considering NBs and solar panels for 4-hour storage duration. In this scenario, the annual electricity and annual total cost savings are around $25,000-$170,000 and $20,000-$145,000 respectively. The study also obtained results for other scenarios (No solar panels, 2-hour storage duration, 6-hour storage duration). However, the scenario with a 4-hour storage duration SLB and solar panels provides the maximum savings. SLBs are cheaper and offer an acceptable charging/discharging rate for the required power during peak hour demand. The cost breakdown for the 2-hour and 6-hour storage duration BESS are presented in appendix B from **Table 7 to 10**.

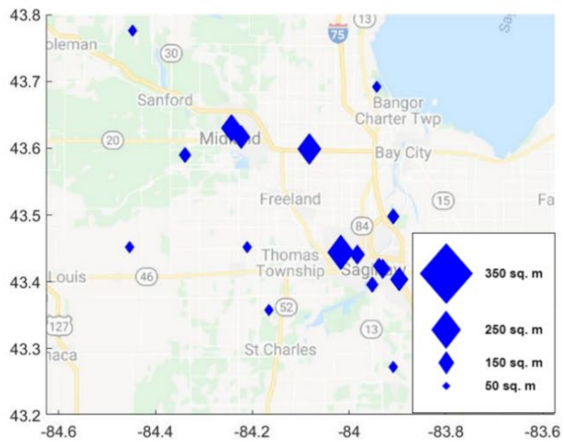


(i) Solar panel area (sq.m)

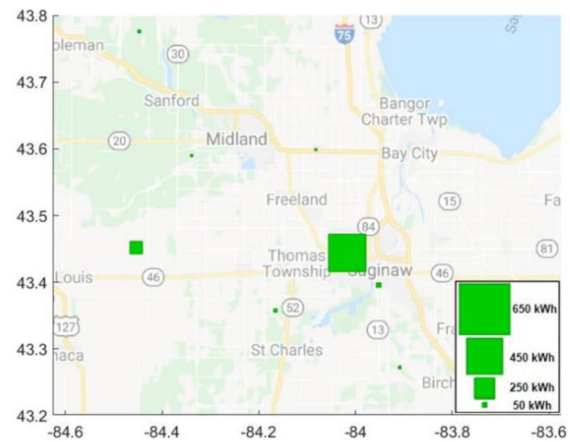


(ii) NB size (kWh)

a) EV load factor=1

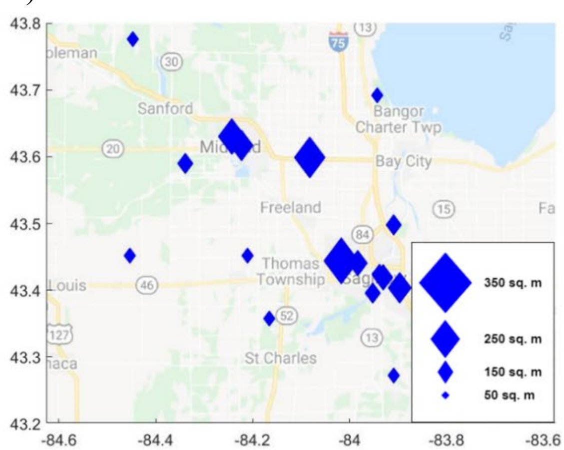


(i) Solar panel area (sq.m)

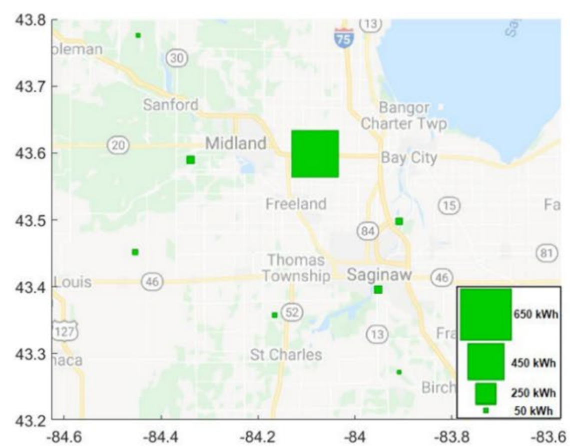


(ii) NB size (kWh)

b) EV load factor=1.5



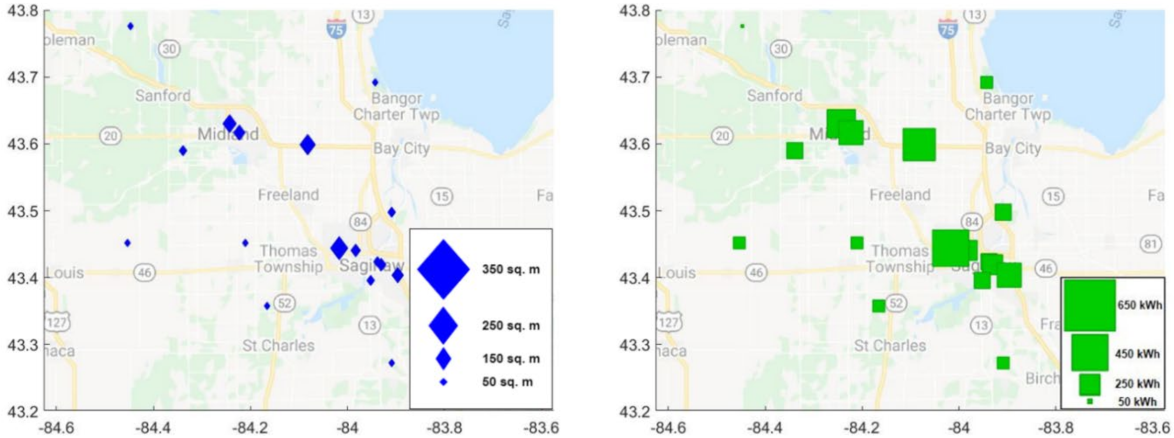
(i) Solar panel area (sq.m)



(ii) NB size (kWh)

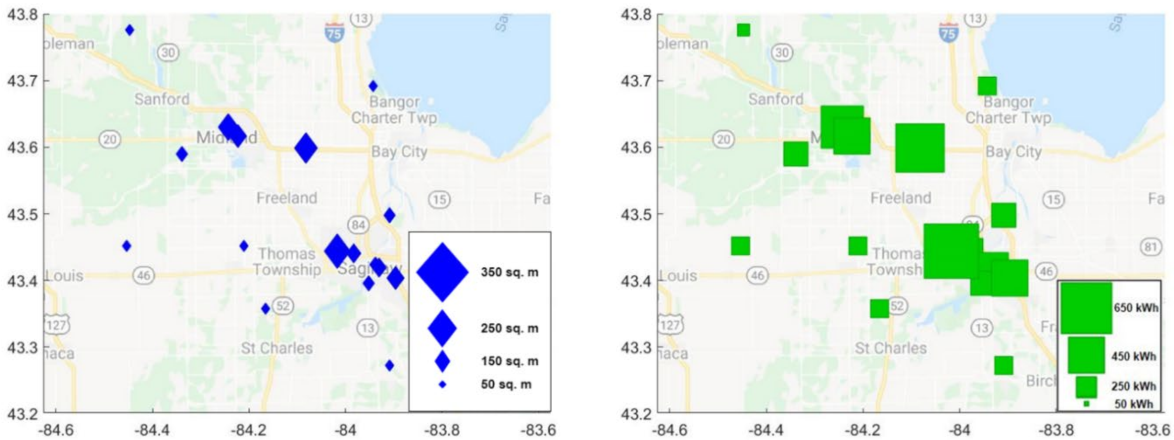
c) EV load factor=2

Figure 6 Size of NB (4 hour storage duration) and solar panels for the city of Saginaw



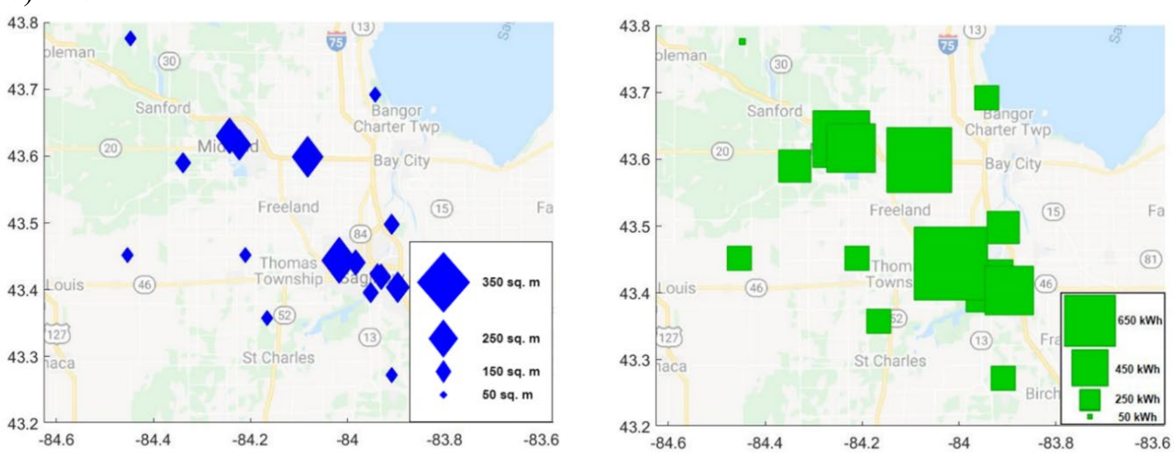
(i) Solar panel area (sq.m) (ii) SLB size (kWh)

a) EV load factor=1



(i) Solar panel area (sq.m) (ii) SLB size (kWh)

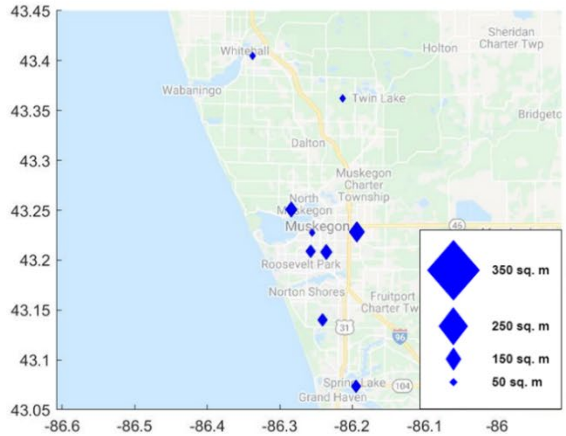
b) EV load factor=1.5



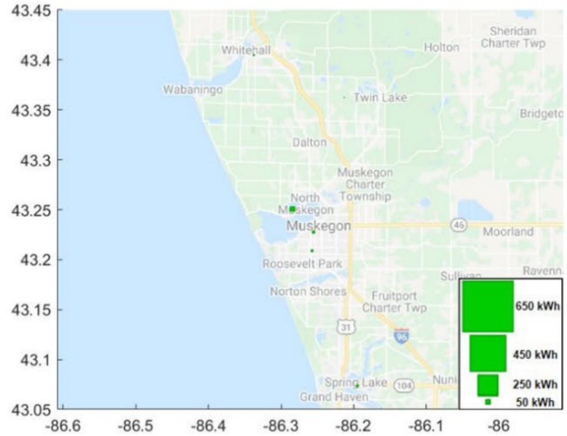
(i) Solar panel area (sq.m) (ii) SLB size (kWh)

c) EV load factor=2

Figure 7 Size of SLB (4 hour storage duration) and solar panels for the city of Saginaw

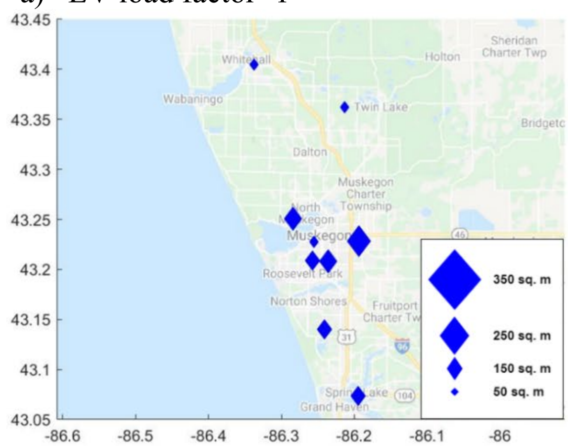


(i) Solar panel area (sq.m)

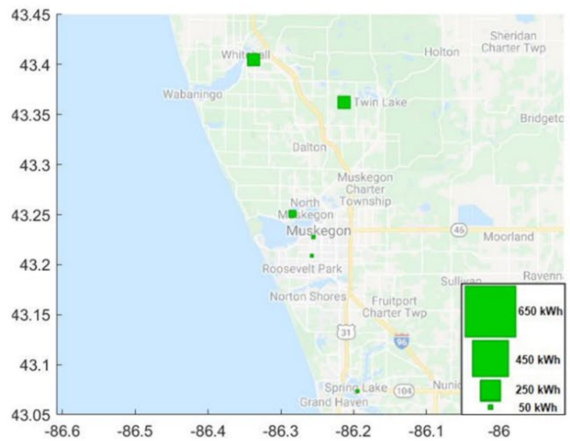


(ii) NB size (kWh)

a) EV load factor=1

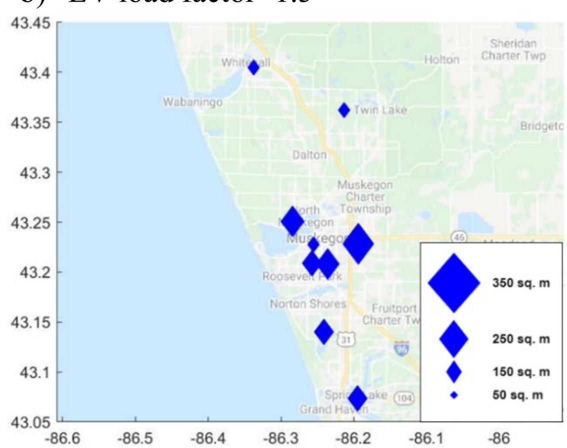


(i) Solar panel area (sq.m)

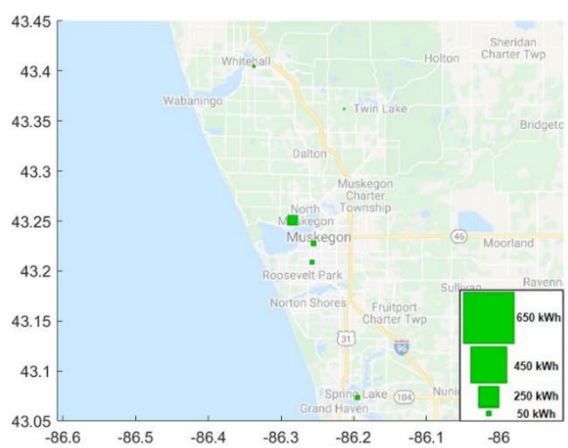


(ii) NB size (kWh)

b) EV load factor=1.5



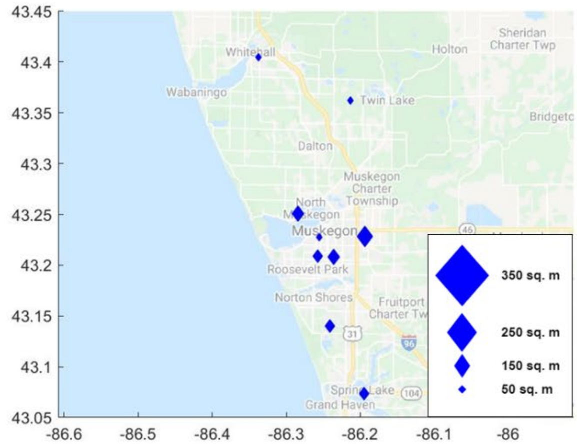
(i) Solar panel area (sq.m)



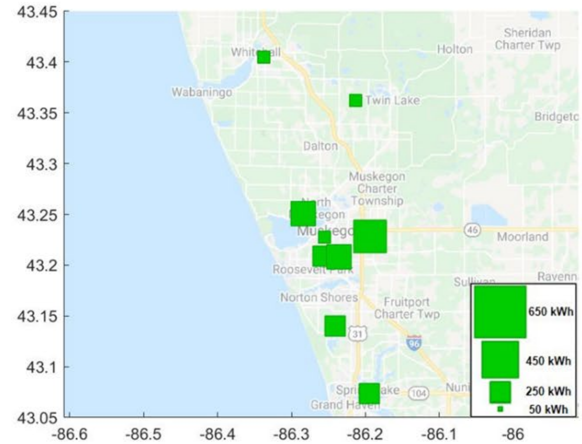
(ii) NB size (kWh)

c) EV load factor=2

Figure 8 Size of NB (4 hour storage duration) and solar panels for the city of Muskegon

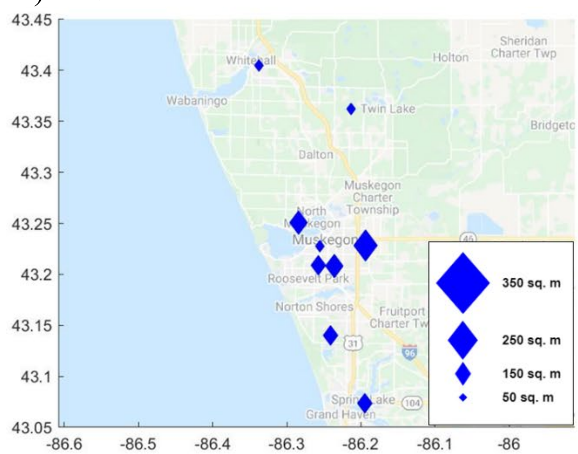


(i) Solar panel area (sq.m)

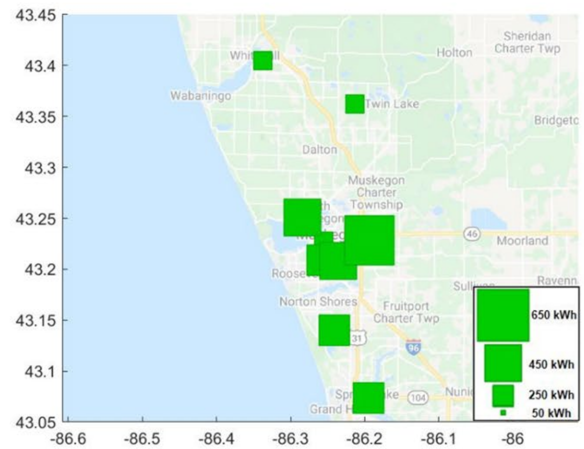


(ii) SLB size (kWh)

a) EV load factor=1

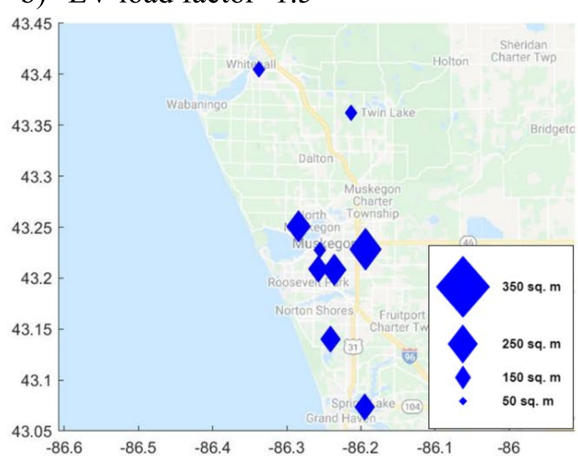


(i) Solar panel area (sq.m)

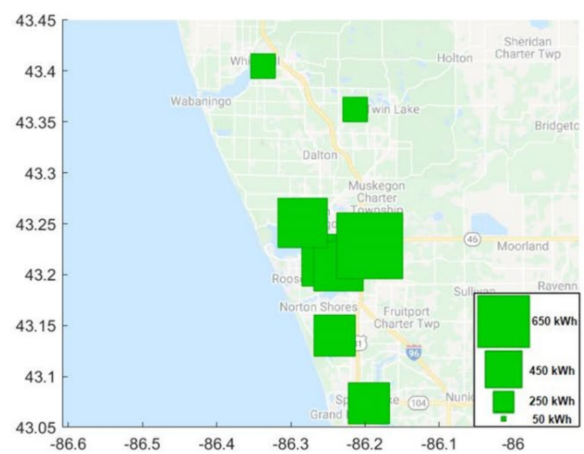


(ii) SLB size (kWh)

b) EV load factor=1.5



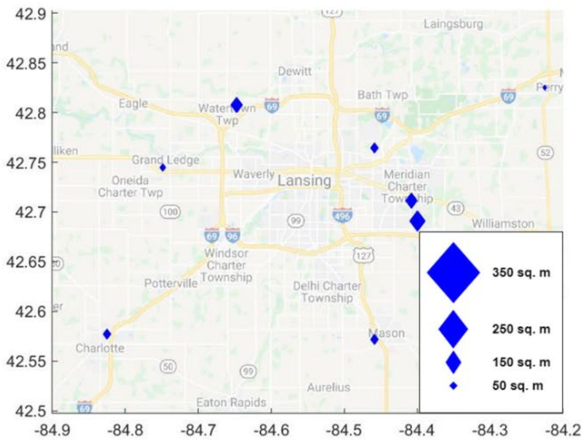
(i) Solar panel area (sq.m)

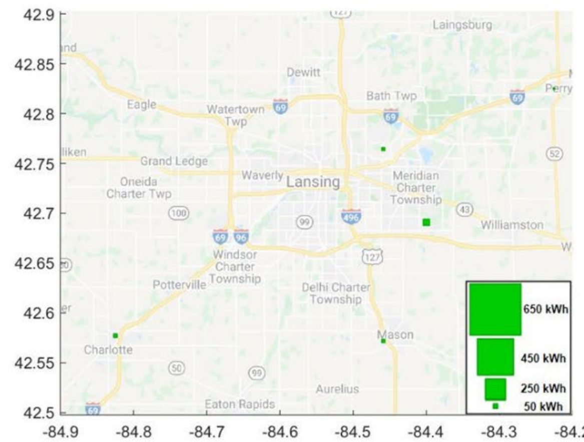


(ii) SLB size (kWh)

c) EV load factor=2

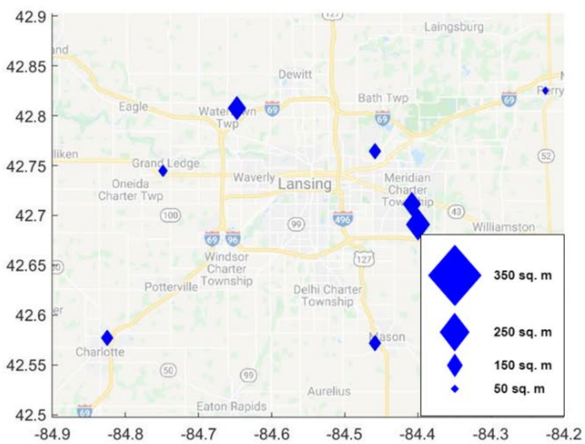
Figure 9 Size of SLB (4 hour storage duration) and solar panels for the city of Muskegon

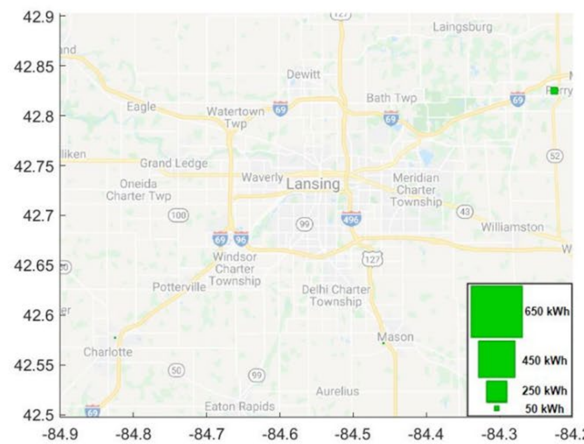




(i) Solar panel area (sq.m) (ii) NB size (kWh)

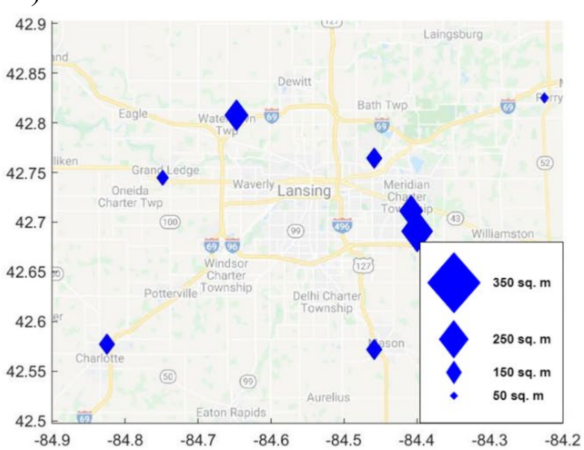
a) EV load factor=1

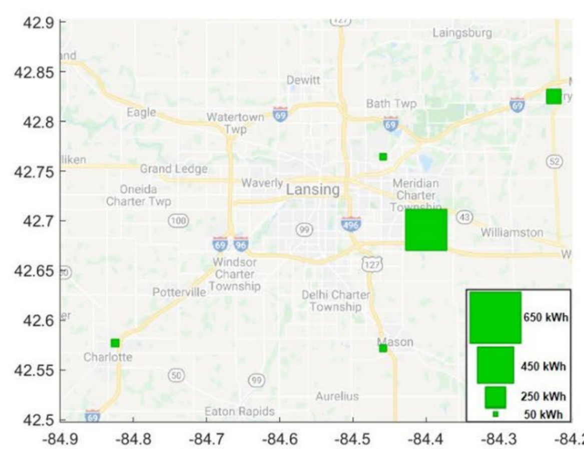




(i) Solar panel area (sq.m) (ii) NB size (kWh)

b) EV load factor=1.5

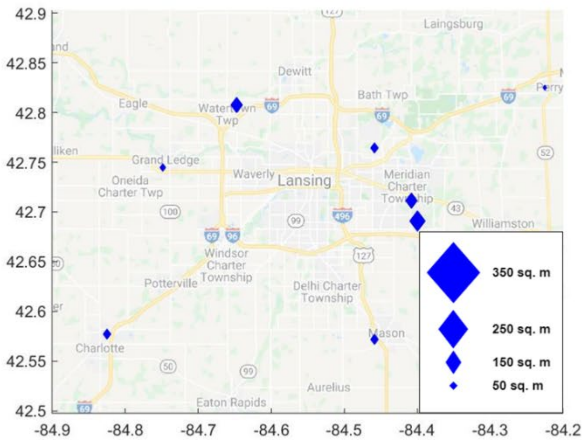




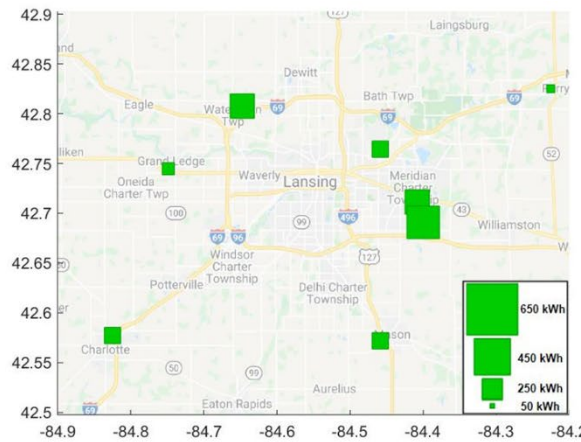
(i) Solar panel area (sq.m) (ii) NB size (kWh)

c) EV load factor=2

Figure 10 Size of NB (4 hour storage duration) and solar panels for the city of Lansing

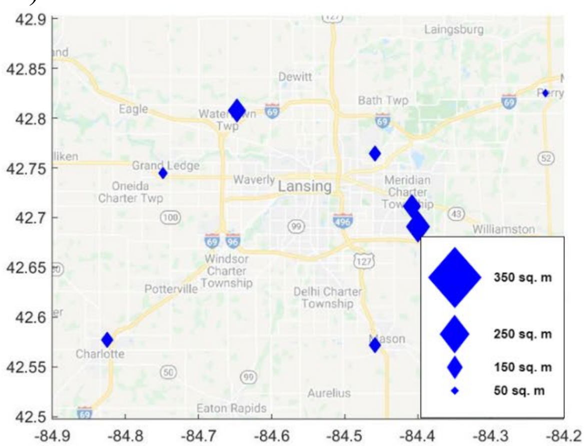


(i) Solar panel area (sq.m)

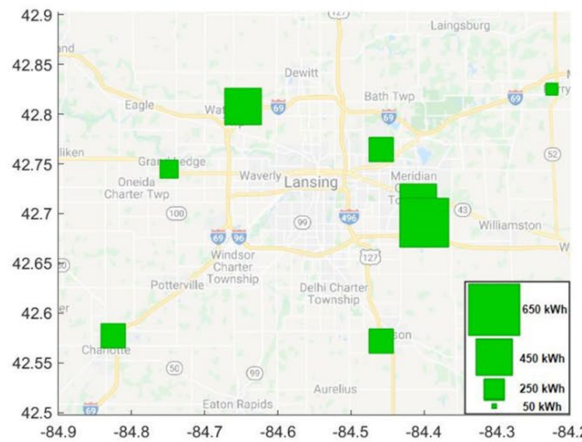


(ii) SLB size (kWh)

a) EV load factor=1

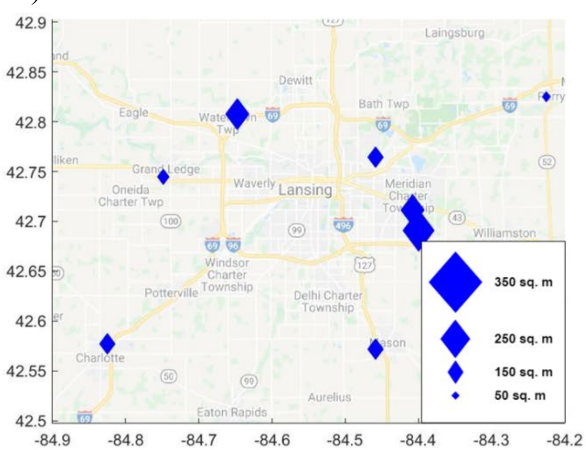


(i) Solar panel area (sq.m)



(ii) SLB size (kWh)

b) EV load factor=1.5



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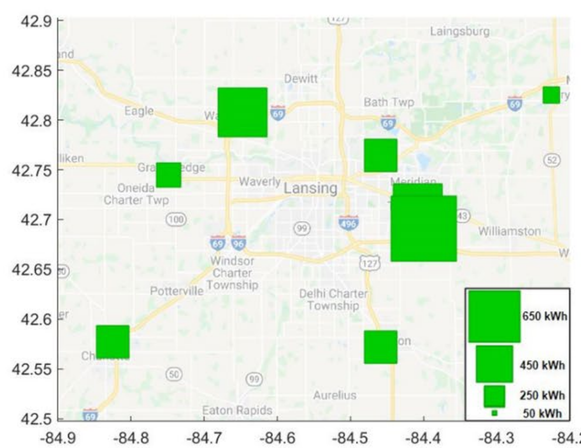
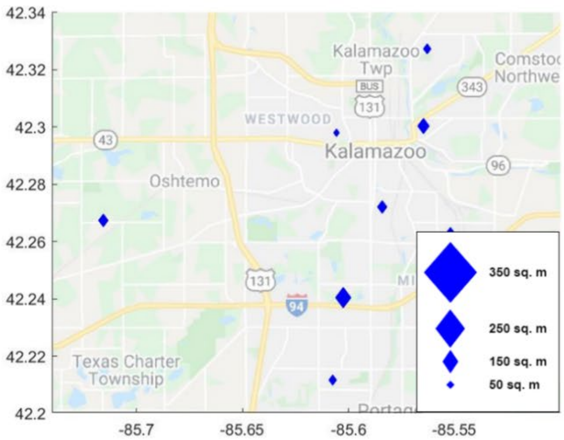


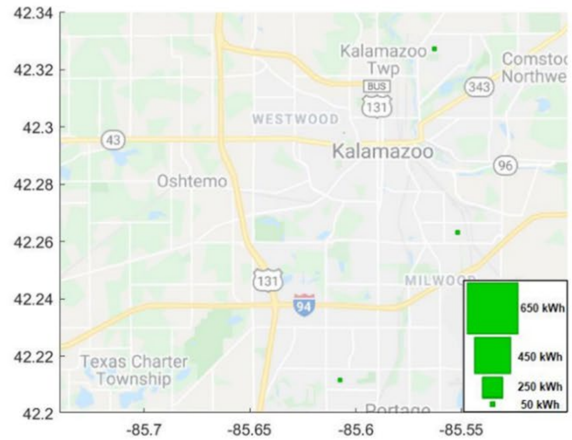
(ii) SLB size (kWh)

c) EV load factor=2

Figure 11 Size of SLB (4 hour storage duration) and solar panels for the city of Lansing

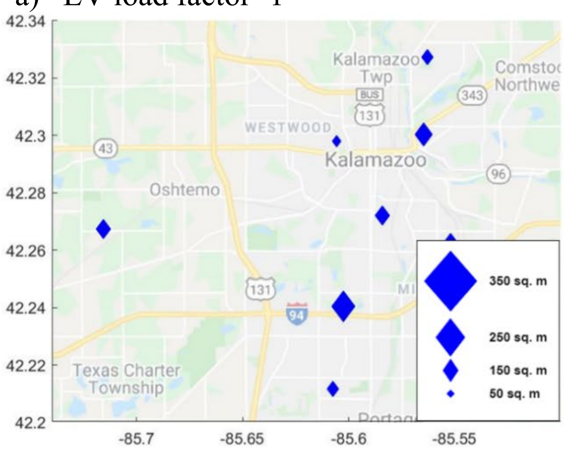


(i) Solar panel area (sq.m)

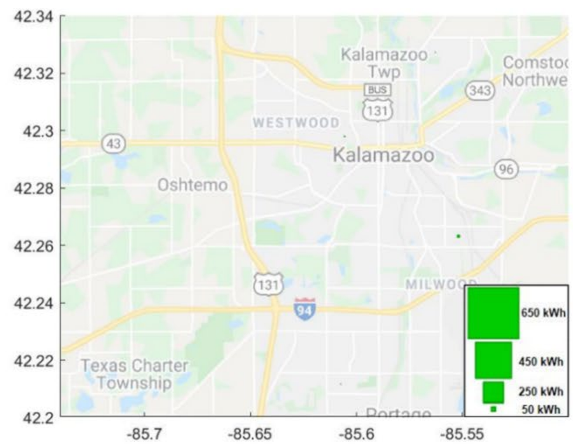


(ii) NB size (kWh)

a) EV load factor=1

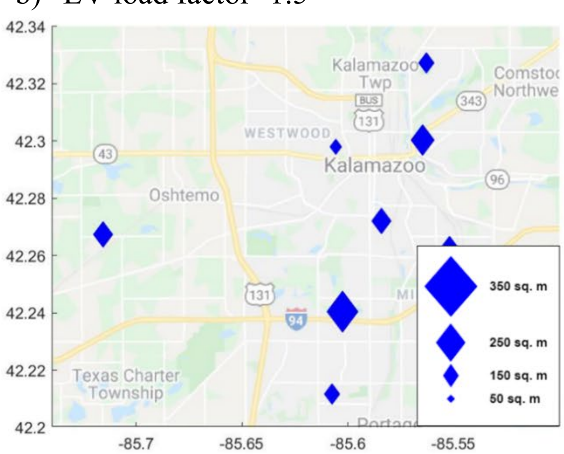


(i) Solar panel area (sq.m)

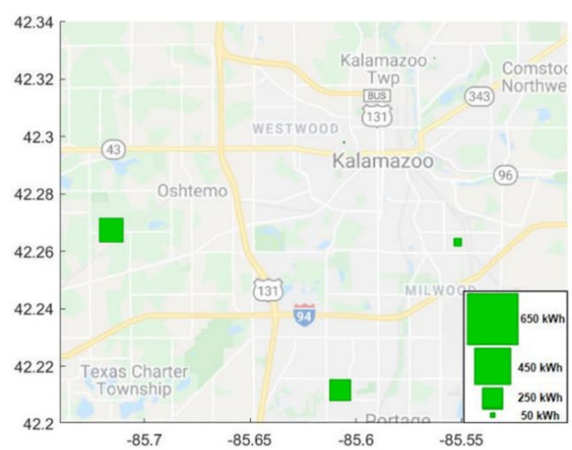


(ii) NB size (kWh)

b) EV load factor=1.5



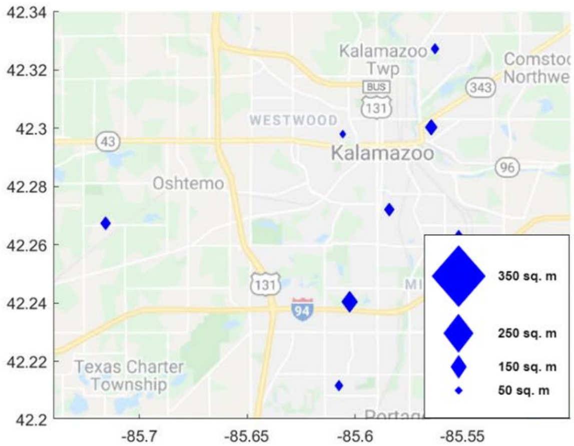
(i) Solar panel area (sq.m)



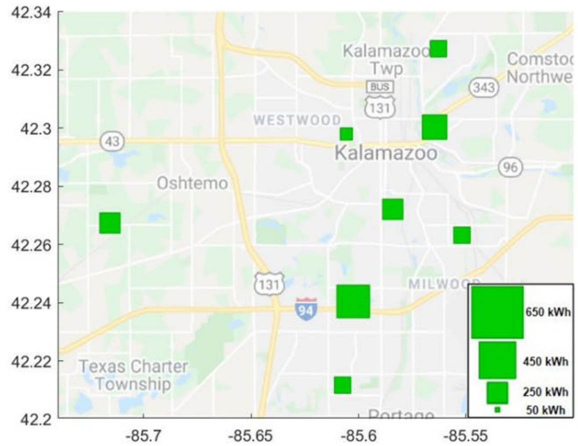
(ii) NB size (kWh)

c) EV load factor=2

Figure 12 Size of NB (4 hour storage duration) and solar panels for the city of Kalamazoo

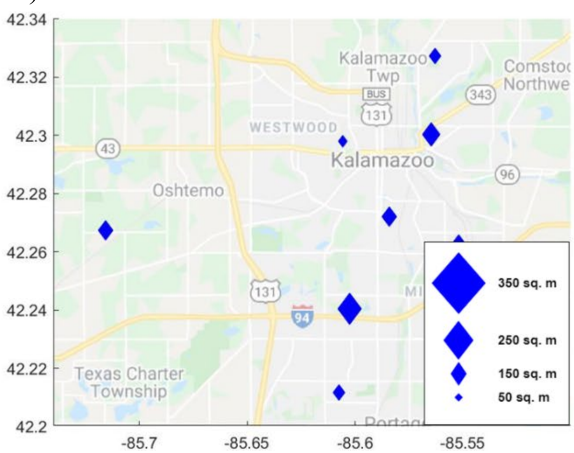


(i) Solar panel area (sq.m)

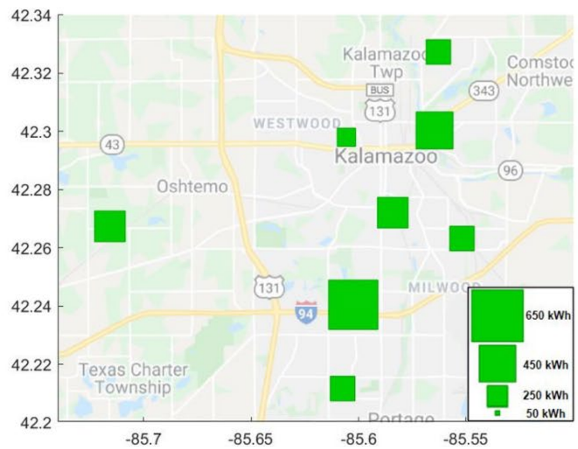


(ii) SLB size (kWh)

a) EV load factor=1

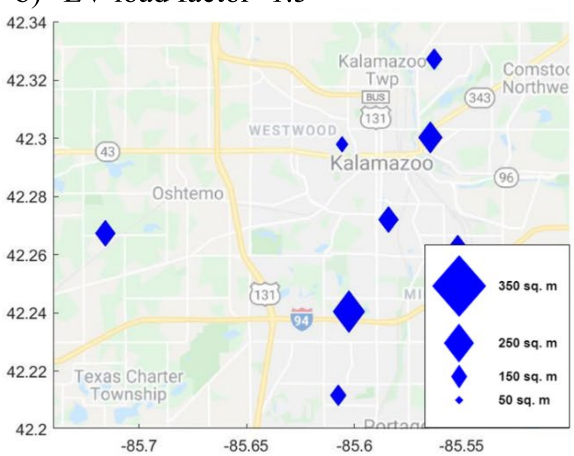


(i) Solar panel area (sq.m)

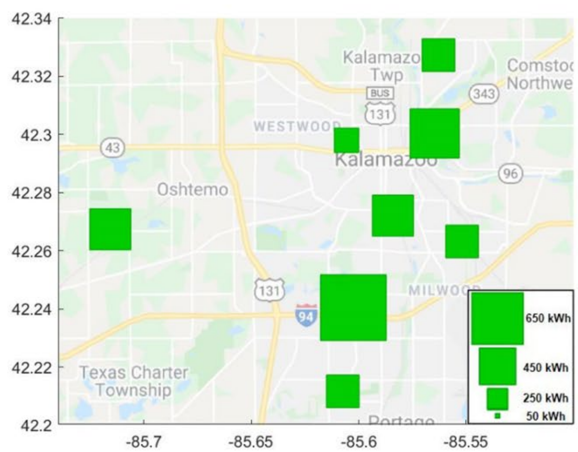


(ii) SLB size (kWh)

b) EV load factor=1.5



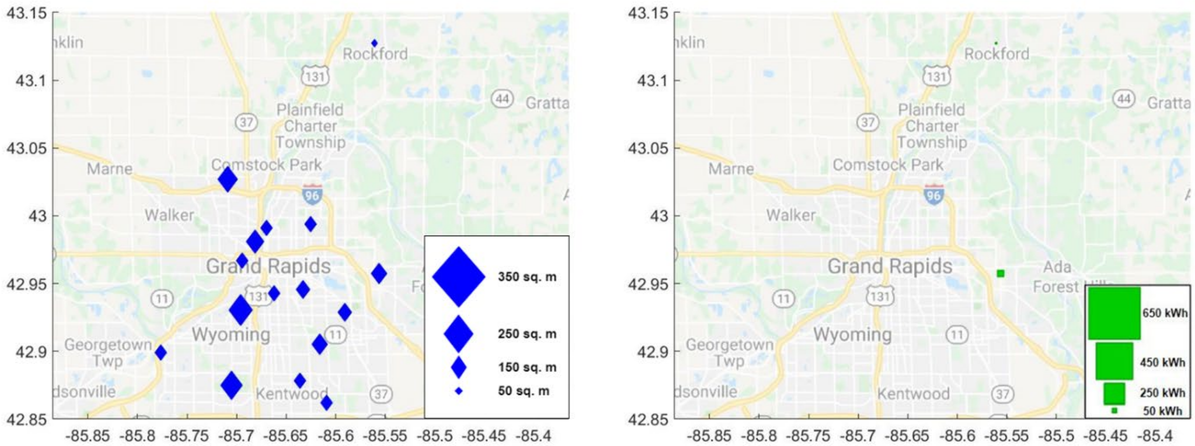
(i) Solar panel area (sq.m)



(ii) SLB size (kWh)

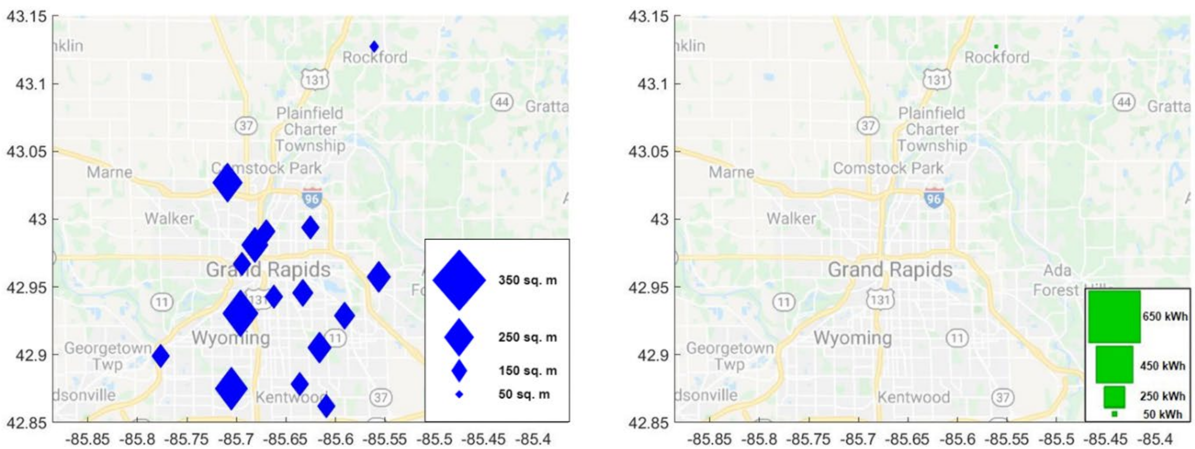
c) EV load factor=2

Figure 13 Size of SLB (4 hour storage duration) and solar panels for the city of Kalamazoo



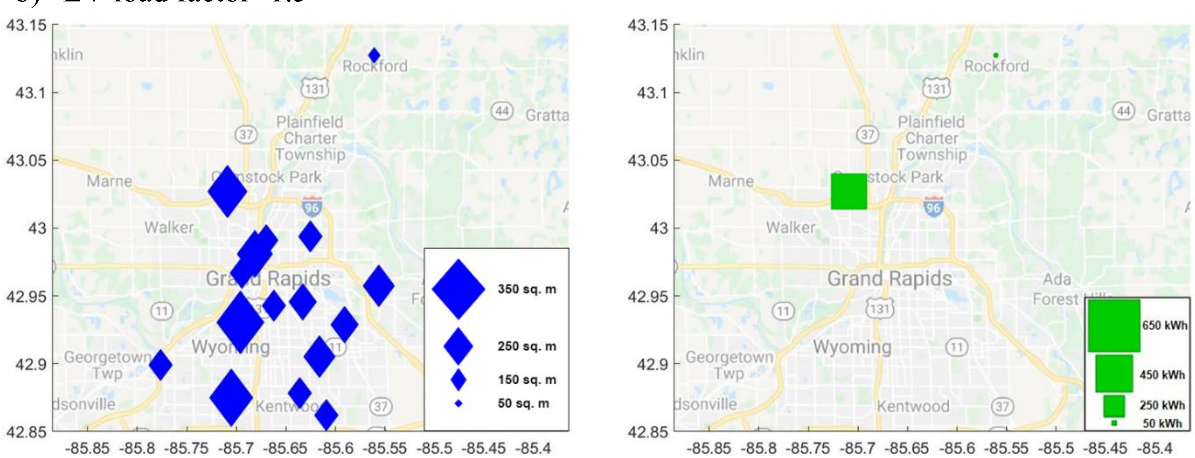
(i) Solar panel area (sq.m) (ii) NB size (kWh)

a) EV load factor=1



(i) Solar panel area (sq.m) (ii) NB size (kWh)

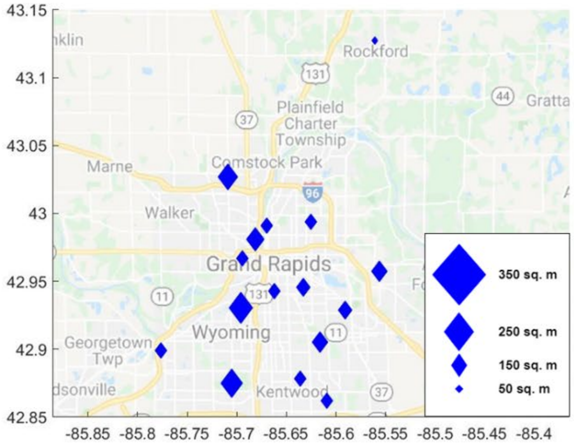
b) EV load factor=1.5



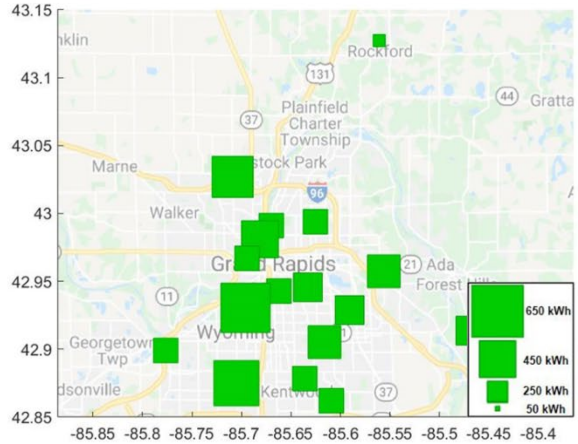
(i) Solar panel area (sq.m) (ii) NB size (kWh)

c) EV load factor=2

Figure 14 Size of NB (4 hour storage duration) and solar panels for the city of Grand Rapids

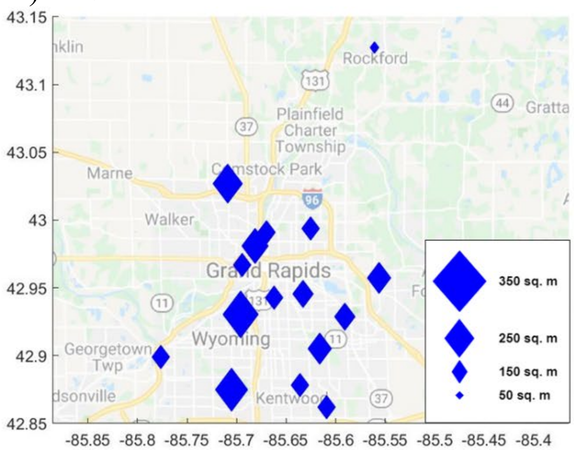


(i) Solar panel area (sq.m)

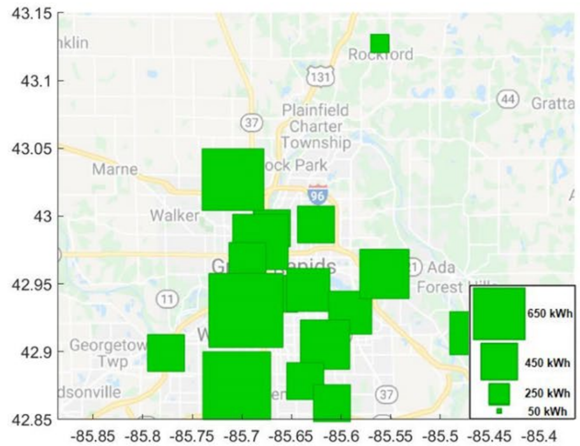


(ii) SLB size (kWh)

a) EV load factor=1

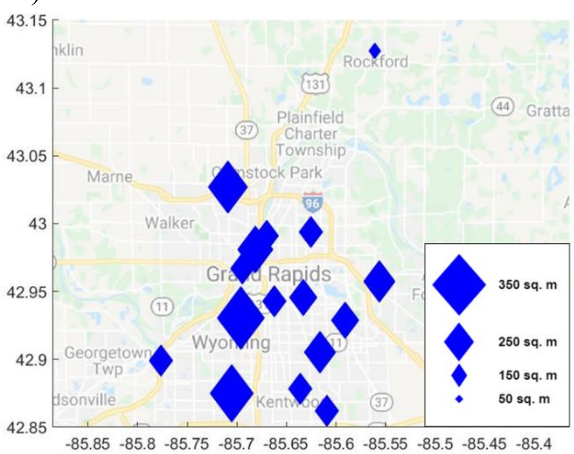


(i) Solar panel area (sq.m)

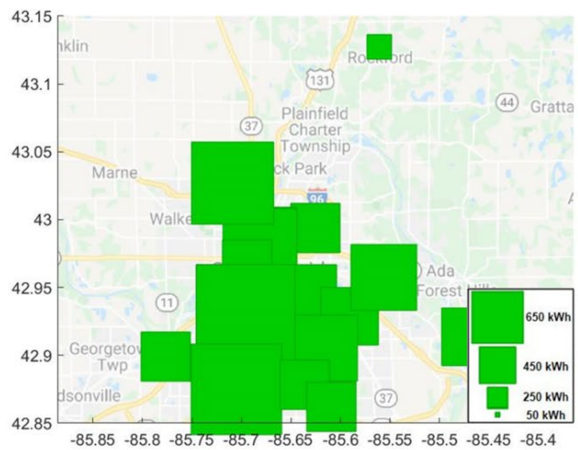


(ii) SLB size (kWh)

b) EV load factor=1.5



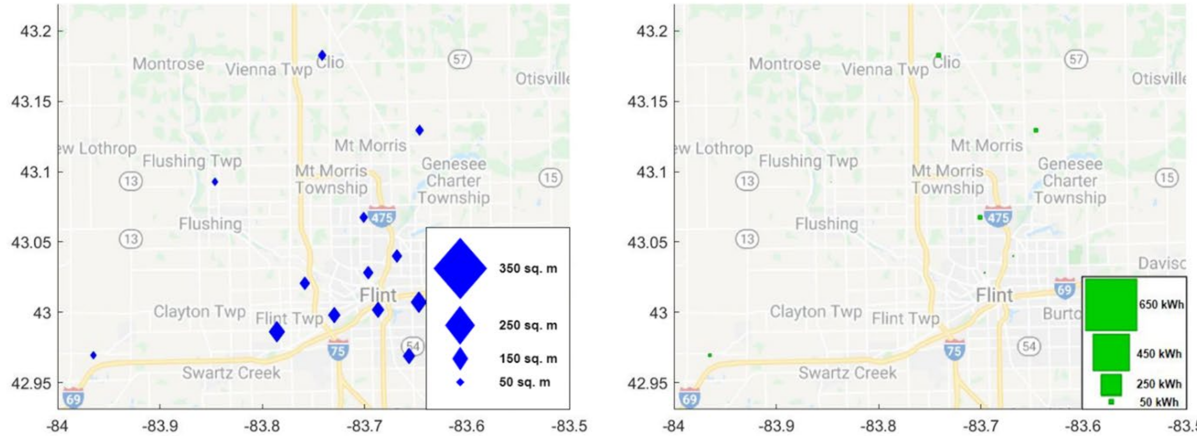
(i) Solar panel area (sq.m)



(ii) SLB size (kWh)

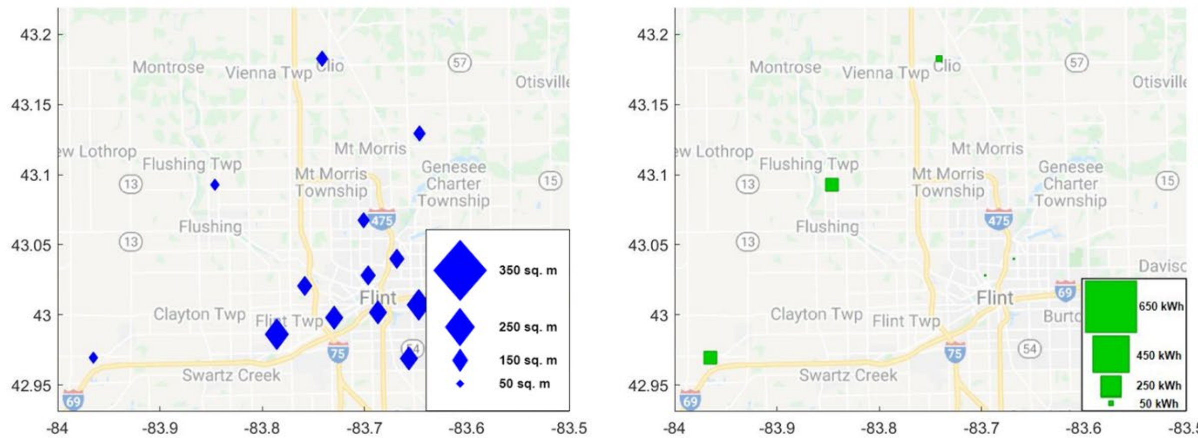
c) EV load factor=2

Figure 15 Size of SLB (4 hour storage duration) and solar panels for the city of Grand Rapids



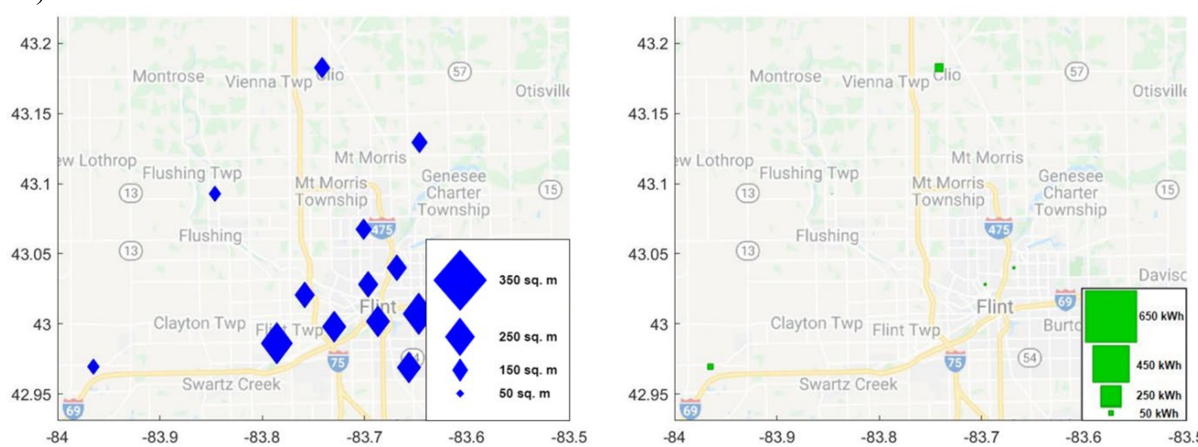
(i) Solar panel area (sq.m) (ii) NB size (kWh)

a) EV load factor=1



(i) Solar panel area (sq.m) (ii) NB size (kWh)

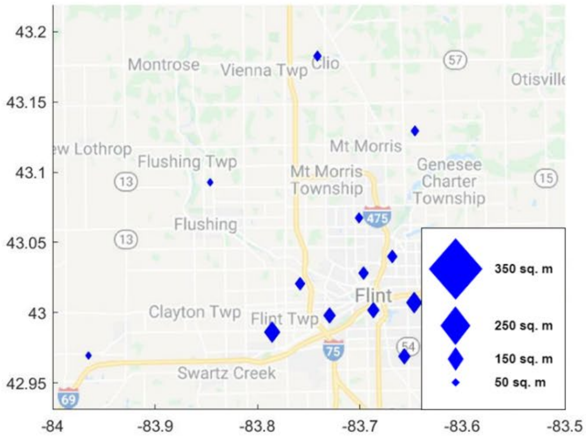
b) EV load factor=1.5



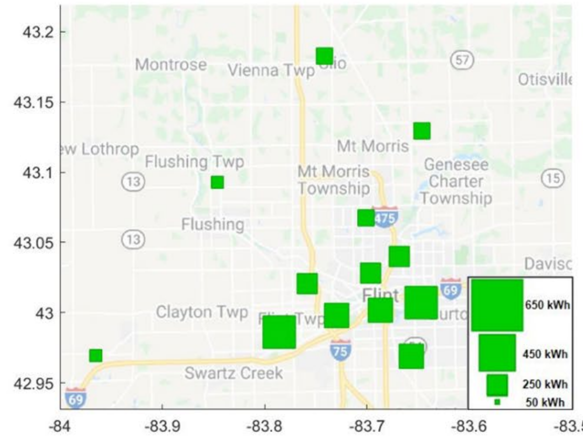
(i) Solar panel area (sq.m) (ii) NB size (kWh)

c) EV load factor=2

Figure 16 Size of NB (4 hour storage duration) and solar panels for the city of Flint

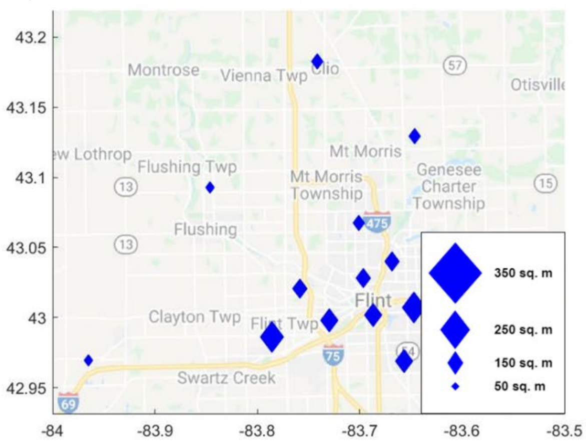


(i) Solar panel area (sq.m)

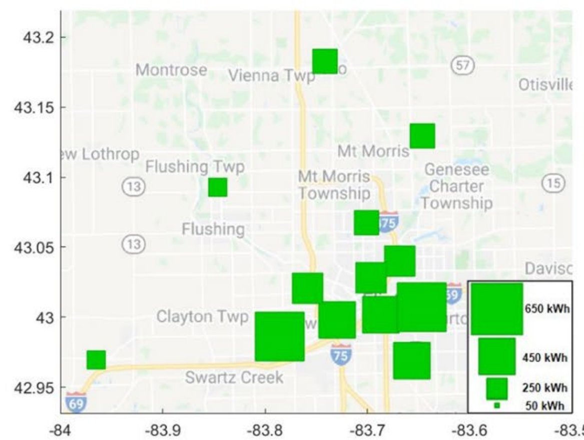


(ii) SLB size (kWh)

a) EV load factor=1

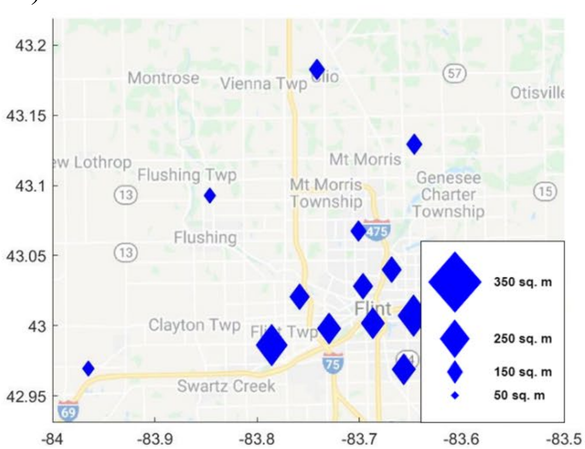


(i) Solar panel area (sq.m)

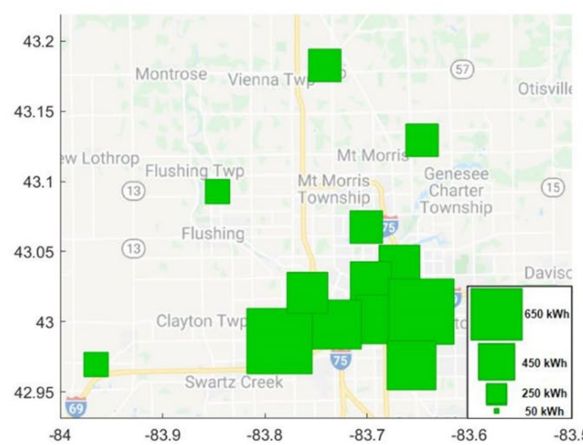


(ii) SLB size (kWh)

b) EV load factor=1.5



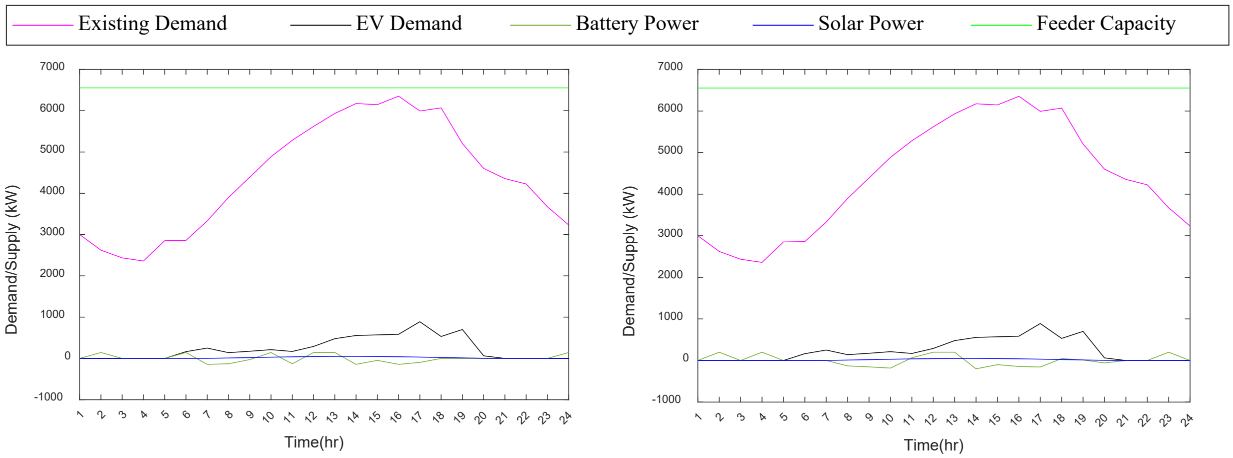
(i) Solar panel area (sq.m)



(ii) SLB size (kWh)

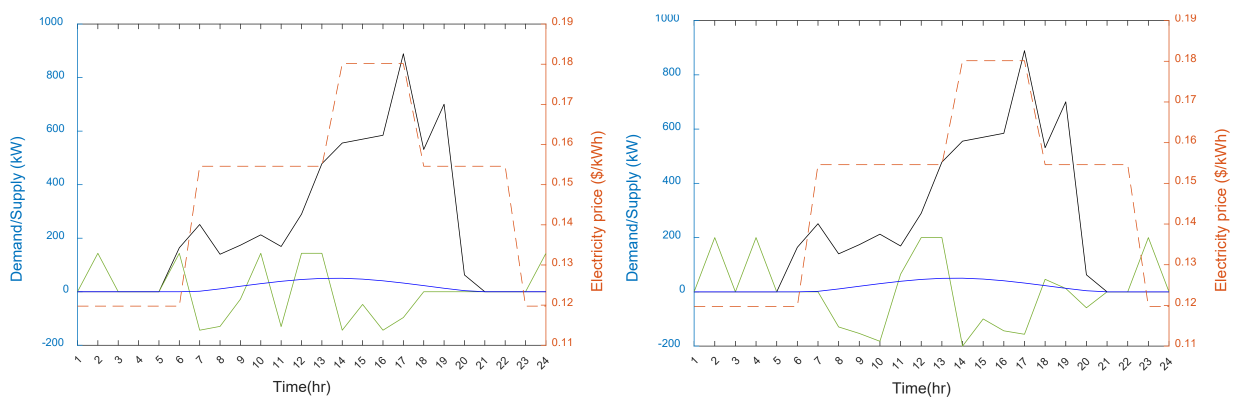
c) EV load factor=2

Figure 17 Size of SLB (4-hour storage duration) and solar panels for the city of Flint



1. NB 2. SLB

Figure 18 Daily demand and supply variations at Grid level for the EV load factor of 2, during the summer season at a location in Saginaw, Michigan



(a) NB (b) SLB

Figure 19 Daily demand and supply variations at DCFC station level for the EV load factor of 2, during the summer season at a location in Saginaw, Michigan

TABLE 5 Cost breakdown for the case of 4 hour SLB and the solar panels in Michigan

Saginaw								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	498	469	207	0	1538	1595	95	63
1.5	755	713	310	0	2247	2334	142	87

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
2	894	937	414	0	2957	3068	189	111
Muskegon								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	273	252	108	0	862	893	50	29
1.5	281	378	163	0	1264	1305	75	44
2	316	504	217	0	1665	1719	100	57
Lansing								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	185	212	91	0	857	882	43	25
1.5	205	318	137	0	1259	1294	64	37
2	219	424	182	0	1662	1706	84	53
Kalamazoo								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	263	246	106	0	975	1005	49	29
1.5	289	370	159	0	1433	1474	73	45
2	314	493	212	0	1890	1943	99	64
Grand Rapids								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	397	711	306	0	2799	2873	141	81
1.5	455	1066	458	0	4141	4249	213	121
2	506	1421	611	0	5484	5624	284	165
Flint								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	286	407	175	0	1518	1563	81	47
1.5	326	610	262	0	2231	2294	121	70
2	368	814	350	0	2944	3026	162	93

TABLE 6 Cost breakdown for the case of 4 hour NB and the solar panels in Michigan

Saginaw								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	502	94	207	0	1572	1603	61	55
1.5	793	129	310	0	2299	2346	90	75
2	916	160	414	0	3027	3083	119	96
Muskegon								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	277	24	108	0	882	897	30	25
1.5	291	77	163	0	1291	1312	48	37
2	323	49	217	0	1705	1727	60	49
Lansing								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	185	36	91	0	873	885	27	22
1.5	219	17	137	0	1286	1299	37	32
2	226	143	182	0	1689	1713	57	46
Kalamazoo								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	267	30	106	0	994	1009	30	25
1.5	299	8	159	0	1464	1480	42	39
2	323	101	212	0	1926	1952	63	55
Grand Rapids								

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	405	15	306	0	2859	2883	81	71
1.5	483	5	458	0	4233	4265	121	105
2	550	71	611	0	5602	5646	166	143
Flint								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	294	38	175	0	1551	1569	48	41
1.5	330	65	262	0	2279	2304	73	60
2	380	34	350	0	3011	3038	95	81

CONCLUSION

The rapid growth in EVs will necessitate the growth of EV fast-charging infrastructure. However, this will increase the electricity demand which might overload the electric grid. To counter this effect, electric grid upgrades or other DER might be required to support the rising EV demand. An optimization model has been developed to estimate the optimum investment technology to support EV charging demand at DCFC charging stations. The different investment technology includes installation and purchase of ESS (NBs, SLBs, flywheels), solar panels, cost of electric grid network upgrade, and cost of buying/selling electricity from/to the electric grid. A discrete time-dependent model is developed to capture the spatiotemporal demand (EV demand and existing demand), electric grid distribution network, and capacity constraints, and seasonal impacts of solar radiation intensity, electricity rate, and electricity demand. The model is implemented to consider the expected EV charging in 6 major cities in Michigan by the year 2030. The study also did sensitivity analysis with varying EV demand, storage duration of the batteries, and cost of the ESS. The results indicate that maximizing the area of the solar panels considering site restrictions would maximize the benefits. Further, the Li-ion SLB are proved to be a cost-effective solution compared to other ESS (NB, flywheels, etc.). These SLBs make efficient use of the TOU electricity rate, store the intermittent solar energy, charges during the night, and discharges during peak hours. The optimum charge/discharge schedule of SLBs proposed by the study should be adopted for maximum savings. Both solar panels and SLBs should be provided to substantially save electricity and total annual costs. These savings can be further increased if more area is available to offer solar panels and the ESS.

REFERENCES

Beacon Power, 2021. Beacon Power Flywheel Energy Storage Systems.

BloombergNEF, 2020. Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh [WWW Document]. URL https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/ (accessed 9.21.21).

Chakraborty, S., Vu, H.N., Hasan, M.M., Tran, D.D., El Baghdadi, M., Hegazy, O., 2019. DC-DC converter topologies for electric vehicles, plug-in hybrid electric vehicles and fast charging stations: State of the art and future trends. Energies 12, 1569. https://doi.org/10.3390/en12081569

Cole, W., Frazier, A.W., Augustine, C., 2021. Cost Projections for Utility-Scale Battery Storage: 2021 Update. NREL TP-6A20-79236.

EASE, (European Association for Energy Storage), 2022. Energy Storage Technologies [WWW Document]. URL https://ease-storage.eu/energy-storage/technologies/ (accessed 3.5.22).

Ehnberg, J.S.G., Bollen, M.H.J., 2005. Simulation of global solar radiation based on cloud observations, in: Solar Energy. Pergamon, pp. 157–162. https://doi.org/10.1016/j.solener.2004.08.016

Feldman, D., Ramasamy, V., Fu, R., Ramdas, A., Desai, J., Margolis, R., 2021. U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020.

Francfort, J., Garetson, T., Karner, D., Salisbury, S.D., Smart, J.G., 2017. Considerations for Corridor and Community DC Fast Charging Complex System Design. Idaho Falls, ID (United States). https://doi.org/10.2172/1484708

Gallinaro, S., 2020. Energy Storage Systems Boost Electric Vehicles' Fast Charger Infrastructure [WWW Document]. Analog Devices. URL https://www.analog.com/en/technical-articles/energy-storage-systems-boosting-the-electric-vehicles-fast-charger-infrastructure.html# (accessed 4.20.21).

Ghamami, M., Zockaie, A., Miller, S., Kavianipour, M., Fakhrmoosavi, F., Singh, H., Jazlan, F., Shojaei, M., 2020. Electric Vehicle Charger Placement Optimization in Michigan: Phase II-Urban.

Gjelaj, M., Hashemi, S., Andersen, P.B., Traeholt, C., 2020. Optimal infrastructure planning for EV fast-charging stations based on prediction of user behaviour. IET Electr. Syst. Transp. 10, 1–12. https://doi.org/10.1049/IET-EST.2018.5080

Gjelaj, M., Traeholt, C., Hashemi, S., Andersen, P.B., 2017a. DC Fast-charging stations for EVs controlled by a local battery storage in low voltage grids, in: 2017 IEEE Manchester PowerTech, Powertech 2017. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/PTC.2017.7980985

Gjelaj, M., Træholt, C., Hashemi, S., Andersen, P.B., 2017b. Optimal design of DC fast-charging stations for EVs in low voltage grids, in: 2017 IEEE Transportation and Electrification Conference and Expo, ITEC 2017. Institute of Electrical and Electronics Engineers Inc., pp. 684–689. https://doi.org/10.1109/ITEC.2017.7993352

Gjelaj, M., Traholt, C., Hashemi, S., Andersen, P.B., 2017c. Cost-benefit analysis of a novel DC fast-charging station with a local battery storage for EVs, in: 2017 52nd International Universities Power Engineering Conference, UPEC 2017. Institute of Electrical and Electronics Engineers Inc., pp. 1–6. https://doi.org/10.1109/UPEC.2017.8231973

Hilton, G., Kiaee, M., Bryden, T., Cruden, A., Mortimer, A., 2019. The case for energy storage installations at high rate EV chargers to enable solar energy integration in the UK – An optimised approach. J. Energy Storage 21, 435–444. https://doi.org/10.1016/j.est.2018.12.012

IEA, 2020. Global EV Outlook 2020 [WWW Document]. URL https://www.iea.org/reports/global-ev-outlook-2020 (accessed 4.19.21).

Kamath, D., Arsenault, R., Kim, H.C., Anctil, A., 2020. Economic and Environmental Feasibility of Second-Life Lithium-Ion Batteries as Fast-Charging Energy Storage. Environ. Sci. Technol. 54, 6878–6887. https://doi.org/10.1021/ACS.EST.9B05883/SUPPL_FILE/ES9B05883_SI_001.PDF

Kandil, S.M., Farag, H.E.Z., Shaaban, M.F., El-Sharafy, M.Z., 2018. A combined resource allocation framework for PEVs charging stations, renewable energy resources and distributed energy storage systems. Energy 143, 961–972. https://doi.org/10.1016/j.energy.2017.11.005

Kane, M., 2021. CATL Unveils First-Generation Sodium-Ion Battery [WWW Document]. InsideEVs. URL https://insideevs.com/news/523413/catl-unveils-sodium-ion-battery/ (accessed 12.6.21).

Kavianipour, M., Fakhrmoosavi, F., Singh, H., Ghamami, M., Zockaie, A., Ouyang, Y., Jackson, R., 2021. Electric vehicle fast charging infrastructure planning in urban networks considering daily travel and charging behavior. Transp. Res. Part D Transp. Environ. 93, 102769. https://doi.org/10.1016/j.trd.2021.102769

Khalid, M.R., Alam, M.S., Sarwar, A., Jamil Asghar, M.S., 2019. A Comprehensive review on electric vehicles charging infrastructures and their impacts on power-quality of the utility grid. eTransportation. https://doi.org/10.1016/j.etran.2019.100006

Khanghah, B.Y., Anvari-Moghaddam, A., Guerrero, J.M., Vasquez, J.C., 2017. Combined solar charging stations and energy storage units allocation for electric vehicles by considering uncertainties, in: Conference Proceedings - 2017 17th IEEE International Conference on Environment and Electrical Engineering and 2017 1st IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2017. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/EEEIC.2017.7977806

Knupfer, S., Noffsinger, J., Sahdev, S., 2018. How battery storage can help charge the electric-vehicle market [WWW Document]. McKinsey Co. URL https://www.mckinsey.com/business-functions/sustainability/our-insights/how-battery-storage-can-help-charge-the-electric-vehicle-market (accessed 4.20.21).

Li, S., Wu, H., Bai, X., Yang, S., 2019. Optimal Dispatch for PV-assisted Charging Station of Electric Vehicles. 2019 IEEE PES GTD Gd. Int. Conf. Expo. Asia, GTD Asia 2019 854–859. https://doi.org/10.1109/GTDASIA.2019.8715910

Ma, C.-T., 2019. System Planning of Grid-Connected Electric Vehicle Charging Stations and Key Technologies: A Review. Energies 12, 4201. https://doi.org/10.3390/en12214201

Mongird, K., Fotedar, V., Viswanathan, V., Koritarov, V., Balducci, P., Hadjerioua, B., Alam, J., 2019. Energy Storage Technology and Cost Characterization Report.

Morrow, K., Darner, D., Francfort, J., 2008. U.S. Department of Energy Vehicle Technologies Program -- Advanced Vehicle Testing Activity -- Plug-in Hybrid Electric Vehicle Charging Infrastructure Review. https://doi.org/10.2172/946853

Negarestani, S., Fotuhi-Firuzabad, M., Rastegar, M., Rajabi-Ghahnavieh, A., 2016. Optimal sizing of storage system in a fast charging station for plug-in hybrid electric vehicles. IEEE Trans. Transp. Electrif. 2, 443–453. https://doi.org/10.1109/TTE.2016.2559165

Neubauer, J., Pesaran, A., Williams, B., Ferry, M., Eyer, J., 2012. A Techno-Economic Analysis of PEV Battery Second Use: Repurposed-Battery Selling Price and Commercial and Industrial End-User Value. SAE Int. NREL/CP-5400-53799.

Nicholas, M., Hall, D., 2018. Lessons learned on early electric vehicle fast-charging deployments . Int. Counc. Clean Transp.

Nielsen, L.B., Prahm, L.P., Berkowicz, R., Conradsen, K., 1981. Net incoming radiation estimated from hourly global radiation and/or cloud observations. J. Climatol. 1, 255–272. https://doi.org/10.1002/joc.3370010305

Nizam, M., Wicaksono, F.X.R., 2019. Design and Optimization of Solar, Wind, and Distributed Energy Resource (DER) Hybrid Power Plant for Electric Vehicle (EV) Charging Station in Rural Area. Proceeding - 2018 5th Int. Conf. Electr. Veh. Technol. ICEVT 2018 41–45. https://doi.org/10.1109/ICEVT.2018.8628341

NREL, 2021. Annual Technology Baseline-Commercial PV [WWW Document]. URL https://atb.nrel.gov/electricity/2021/commercial_pv (accessed 2.21.22).

Patel, P., 2021. Sodium-Ion Batteries Poised to Pick Off Large-Scale Lithium-Ion Applications [WWW Document]. IEEE Spectr. URL https://spectrum.ieee.org/sodium-ion-battery (accessed 12.6.21).

Pieltain Fernandez, L., Gomez San Roman, T., Cossent, R., Mateo Domingo, C., Frias, P., 2011. Assessment of the Impact of Plug-in Electric Vehicles on Distribution Networks. IEEE Trans. Power Syst. 26, 206–213. https://doi.org/10.1109/TPWRS.2010.2049133

Rafi, M.A.H., Bauman, J., 2021. A Comprehensive Review of DC Fast-Charging Stations With Energy Storage: Architectures, Power Converters, and Analysis. IEEE Trans. Transp. Electrif. 7, 345–368. https://doi.org/10.1109/TTE.2020.3015743

Richard, L., Petit, M., 2018a. Fast Charging Station with Battery Storage System for EV: Optimal Integration into the Grid. IEEE Power Energy Soc. Gen. Meet. 2018-Augus. https://doi.org/10.1109/PESGM.2018.8585856

Richard, L., Petit, M., 2018b. Fast charging station with battery storage system for EV: Grid services and battery degradation. 2018 IEEE Int. Energy Conf. ENERGYCON 2018 1–6. https://doi.org/10.1109/ENERGYCON.2018.8398744

Schmitt, A., 2016. Parking Takes Up More Space Than You Think [WWW Document]. Streetsblog USA. URL https://usa.streetsblog.org/2016/07/05/parking-takes-up-more-space-than-you-think/ (accessed 9.2.21).

SunEarthTools, 2021. Calculation of sun’s position in the sky for each location on the earth at any time of day [en] [WWW Document]. URL https://www.sunearthtools.com/dp/tools/pos_sun.php?lang=en#annual (accessed 1.28.21).

Ugirumurera, J., Haas, Z.J., 2017. Optimal Capacity Sizing for Completely Green Charging Systems for Electric Vehicles. IEEE Trans. Transp. Electrif. 3, 565–577. https://doi.org/10.1109/TTE.2017.2713098

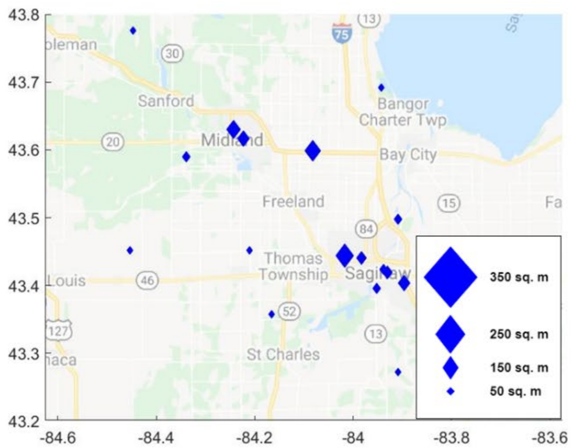
Weather Spark, 2022. Saginaw Climate, Weather By Month, Average Temperature (Michigan, United States) - Weather Spark [WWW Document]. URL https://weatherspark.com/y/16634/Average-Weather-in-Saginaw-Michigan-United-States-Year-Round#Figures-CloudCover (accessed 4.20.22).

Yang, L., Ribberink, H., 2019. Investigation of the potential to improve DC fast charging station economics by integrating photovoltaic power generation and/or local battery energy storage system. Energy 167, 246–259. https://doi.org/10.1016/j.energy.2018.10.147

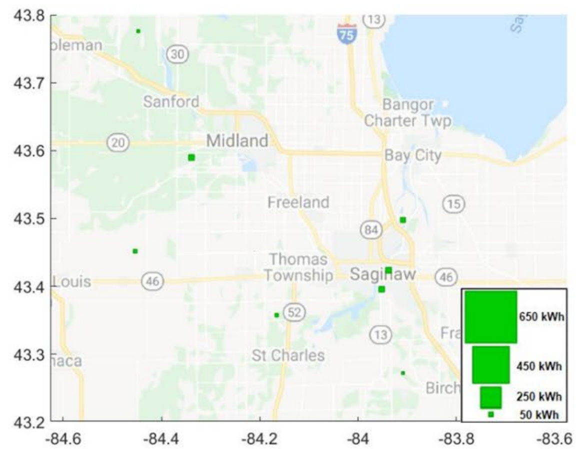
Yilmaz, M., Krein, P.T., 2013. Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles. IEEE Trans. Power Electron. https://doi.org/10.1109/TPEL.2012.2212917

APPENDIX A: SIZE OF THE SOLAR PANELS AND BESS FOR THE 2-HOUR AND 6-HOUR STORAGE DURATION

Saginaw

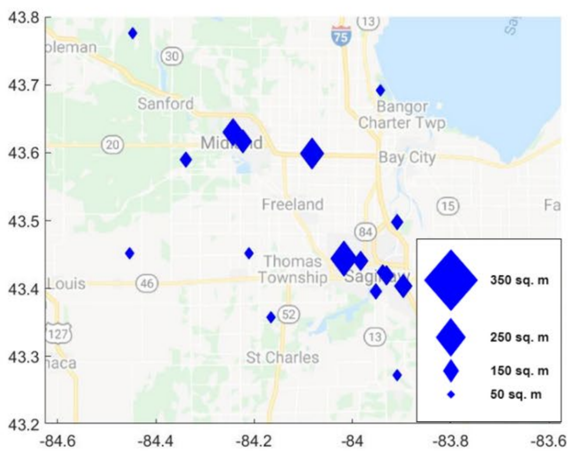


(i) Solar panel area (sq.m)



(ii) NB size (kWh)

a) EV load factor=1



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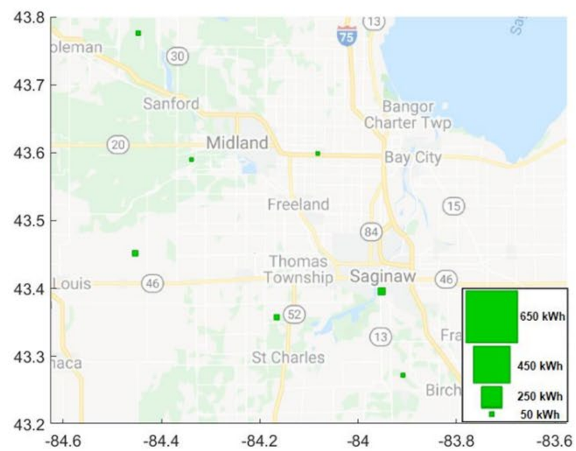
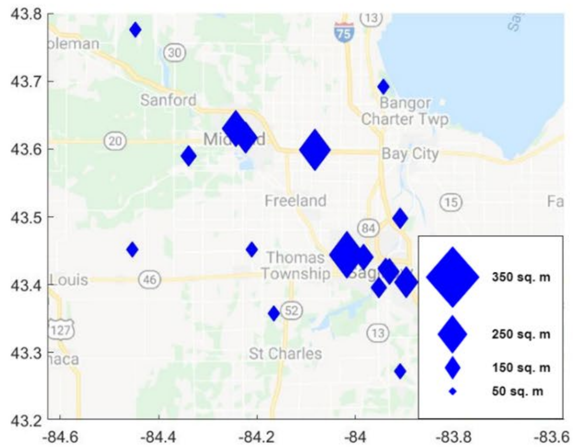
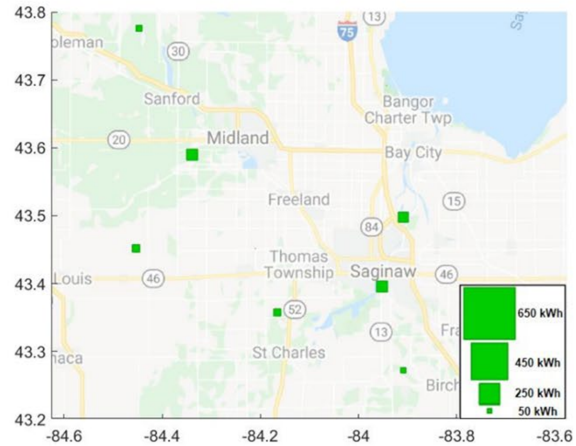


(ii) NB size (kWh)

b) EV load factor=1.5



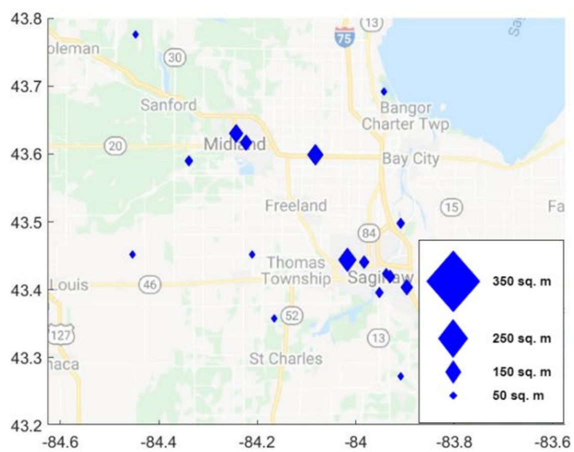
(i) Solar panel area (sq.m)



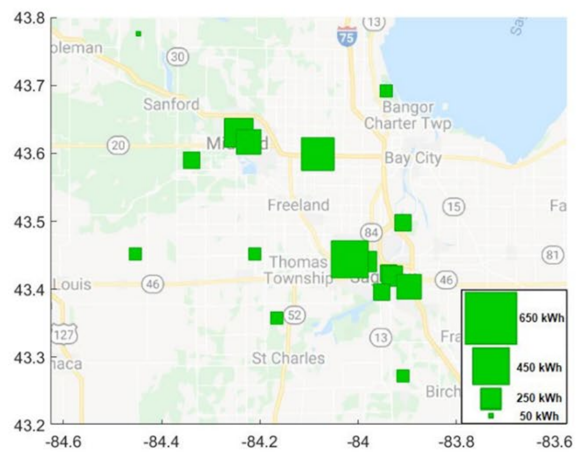
(ii) NB size (kWh)

c) EV load factor=2

Figure 20 Size of NB (6 hour storage duration) and solar panels for the city of Saginaw

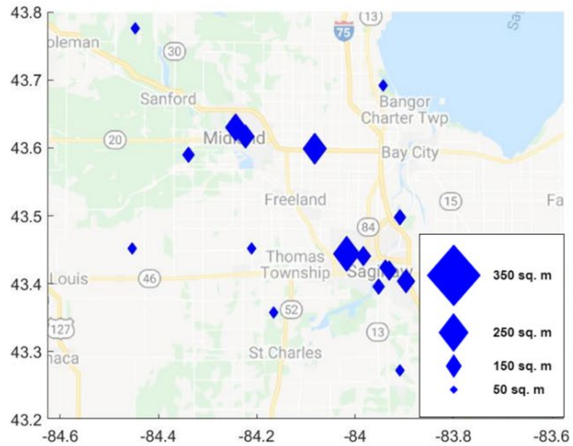


(i) Solar panel area (sq.m)

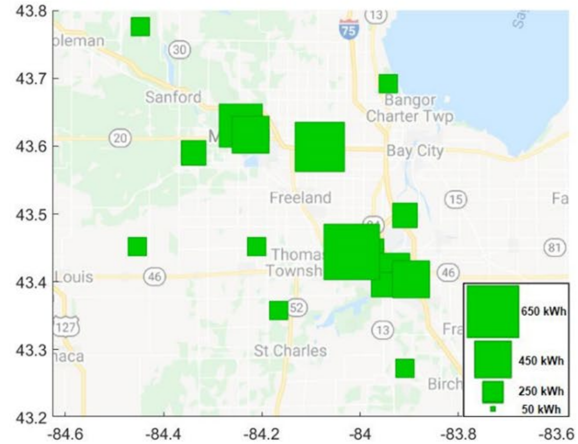


(ii) SLB size (kWh)

a) EV load factor=1

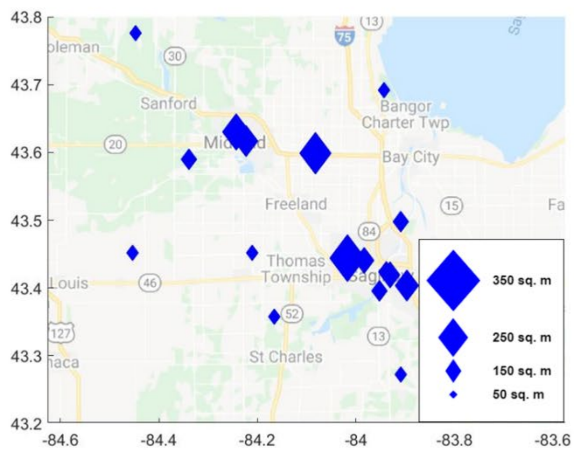


(i) Solar panel area (sq.m)



(ii) SLB size (kWh)

b) EV load factor=1.5



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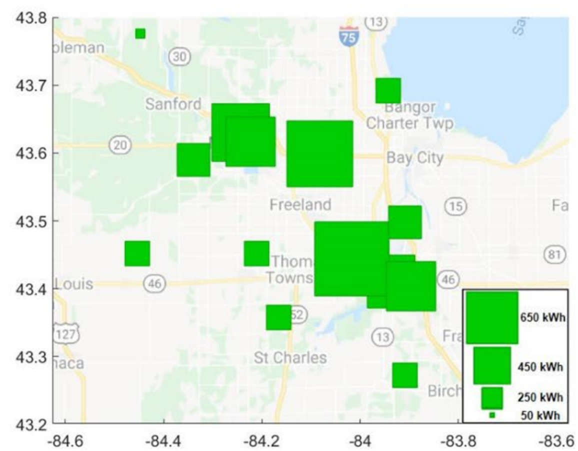
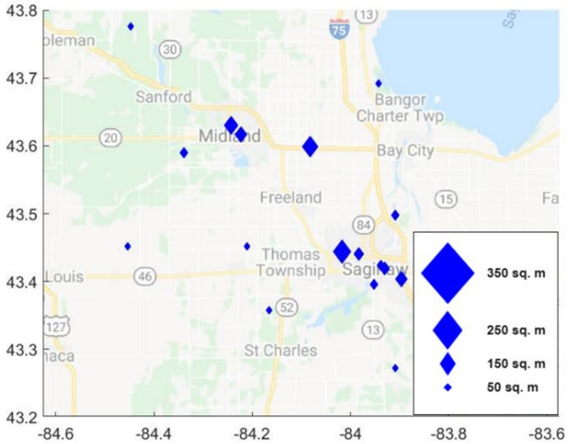


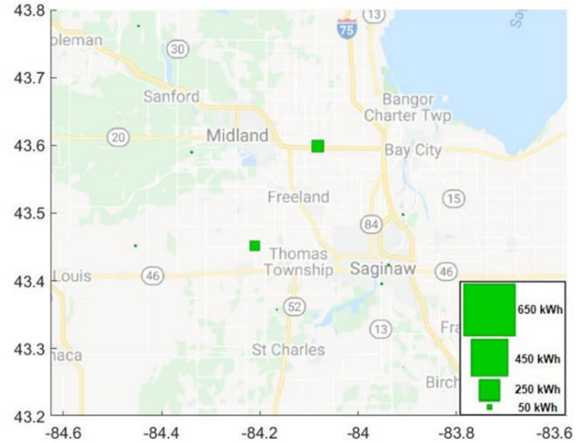
(ii) SLB size (kWh)

c) EV load factor=2

Figure 21 Size of SLB (6 hour storage duration) and solar panels for the city of Saginaw

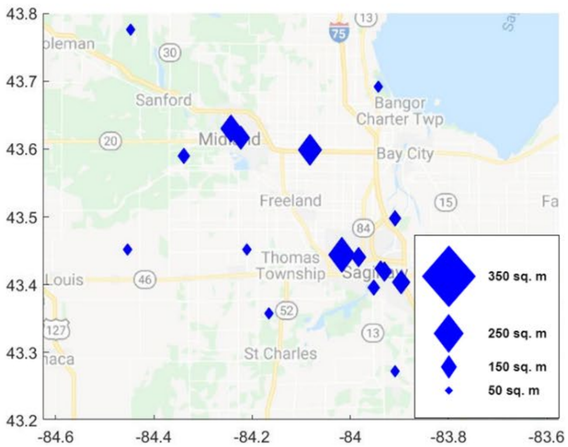


(i) Solar panel area (sq.m)

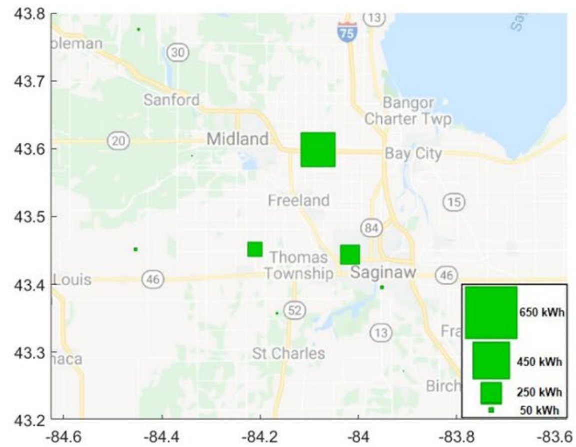


(ii) NB size (kWh)

a) EV load factor=1

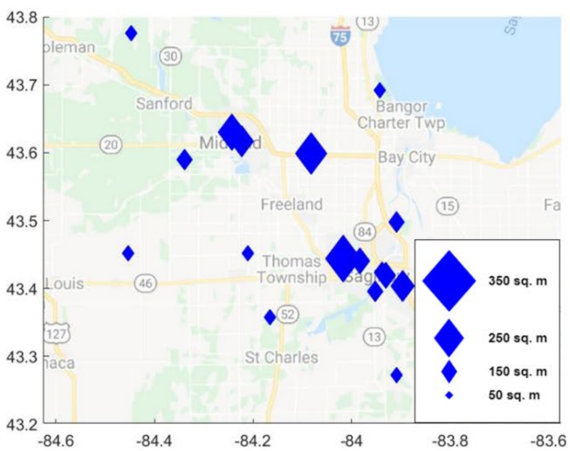


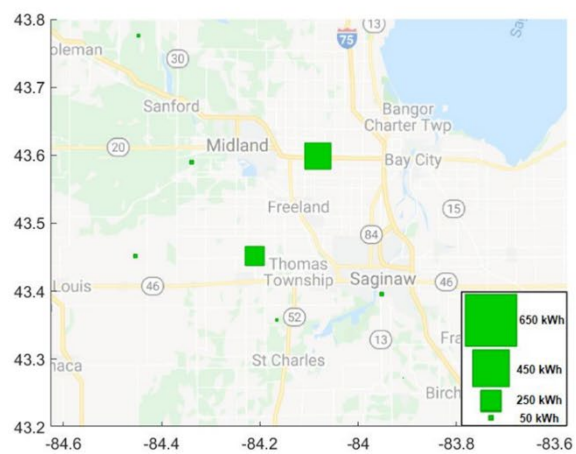
(i) Solar panel area (sq.m)



(ii) NB size (kWh)

b) EV load factor=1.5

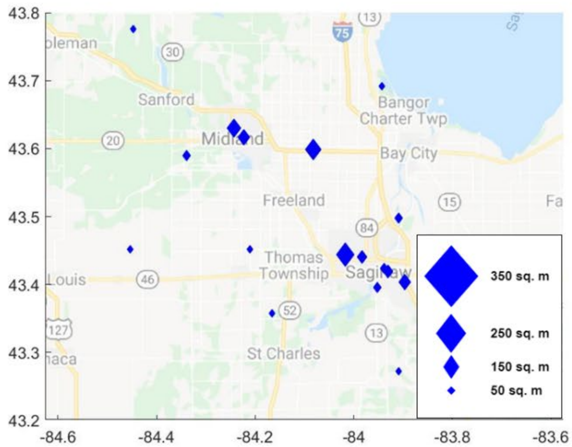




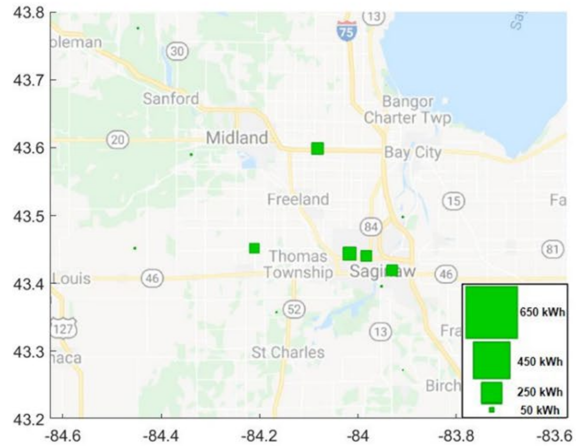
(i) Solar panel area (sq.m) (ii) NB size (kWh)

c) EV load factor=2

Figure 22 Size of NB (2 hour storage duration) and solar panels for the city of Saginaw

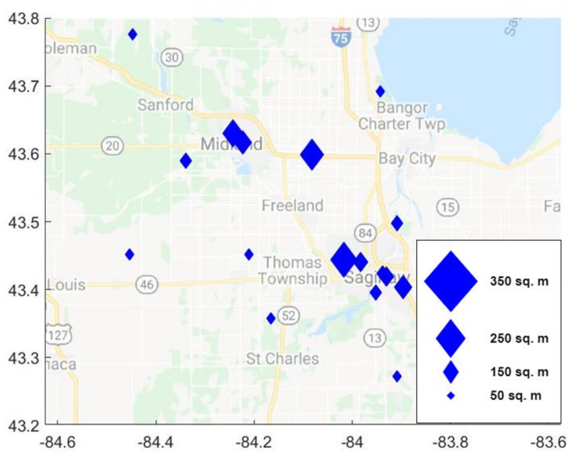


(i) Solar panel area (sq.m)

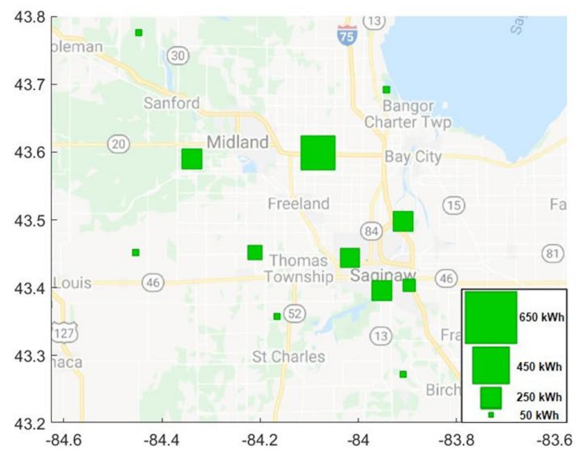


(ii) SLB size (kWh)

a) EV load factor=1

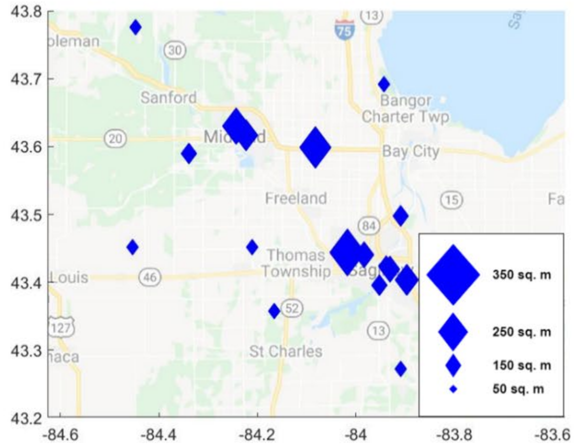


(i) Solar panel area (sq.m)

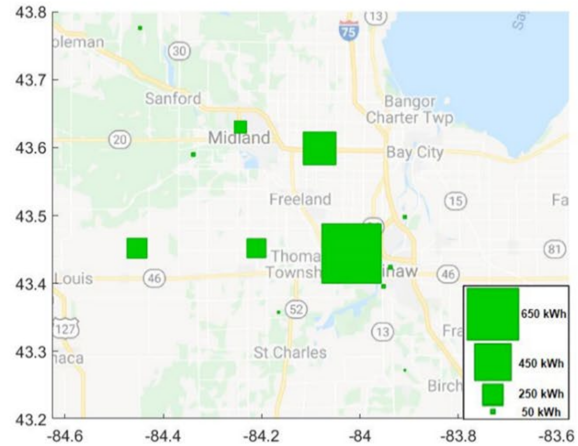


(ii) SLB size (kWh)

b) EV load factor=1.5



(i) Solar panel area (sq.m)

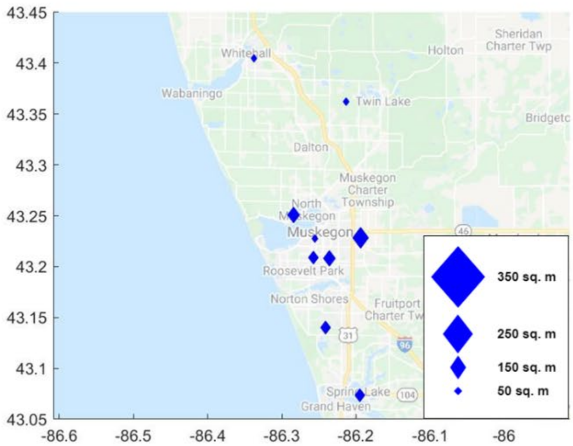


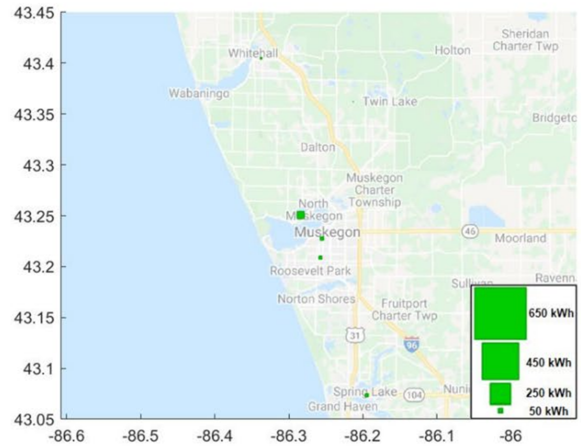
(ii) SLB size (kWh)

c) EV load factor=2

Figure 23 Size of SLB (2 hour storage duration) and solar panels for the city of Saginaw

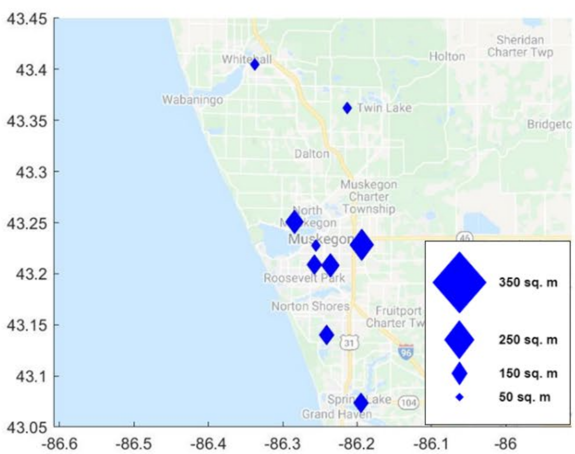
Muskegon

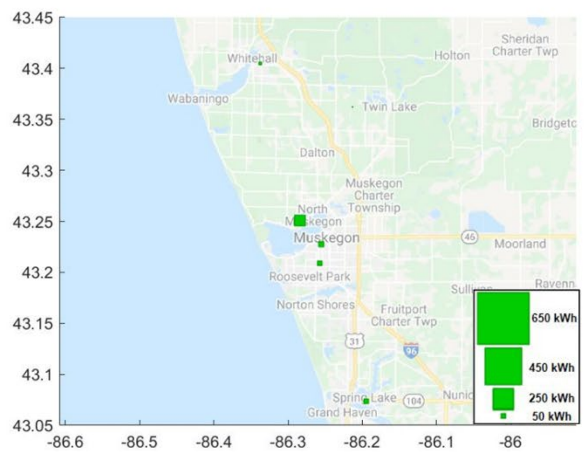




(i) Solar panel area (sq.m) (ii) NB size (kWh)

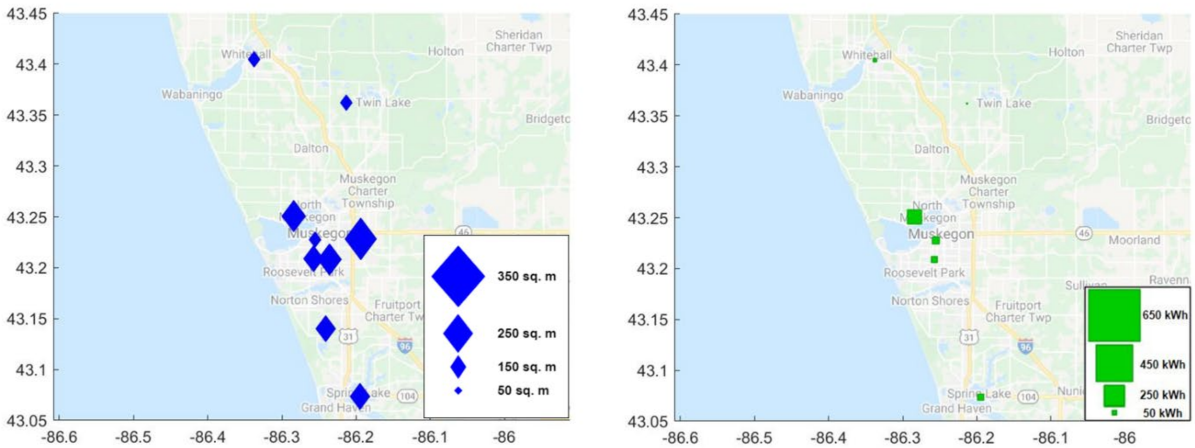
a) EV load factor=1





(i) Solar panel area (sq.m) (ii) NB size (kWh)

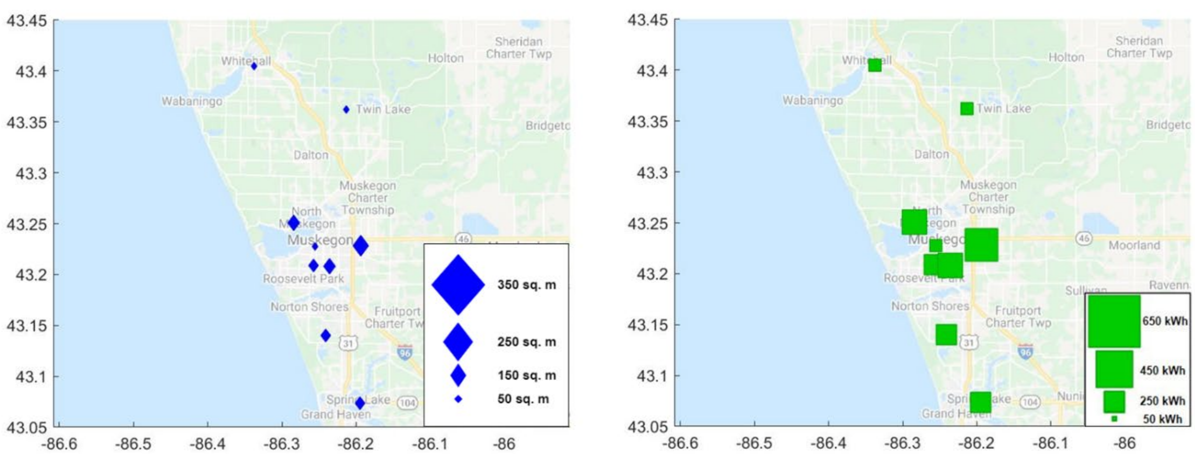
b) EV load factor=1.5



(i) Solar panel area (sq.m) (ii) NB size (kWh)

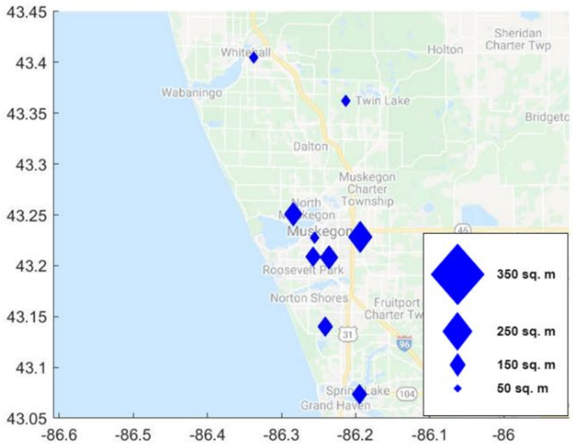
c) EV load factor=2

Figure 24 Size of NB (6 hour storage duration) and solar panels for the city of Muskegon

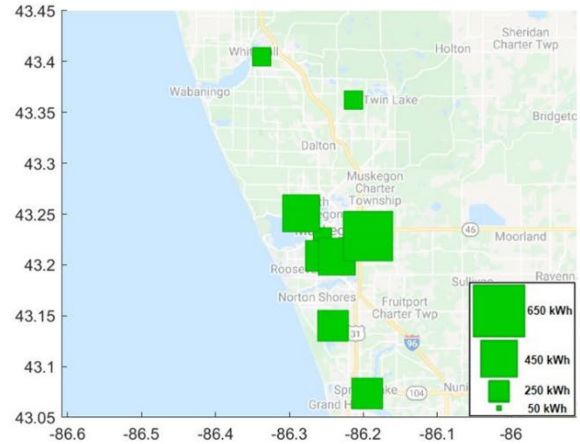


(i) Solar panel area (sq.m) (ii) SLB size (kWh)

a) EV load factor=1

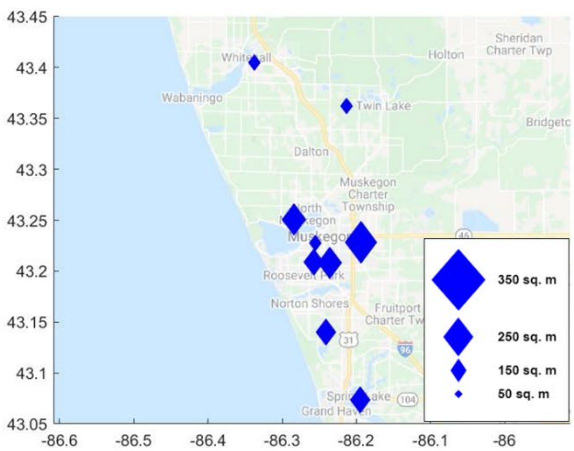


(i) Solar panel area (sq.m)

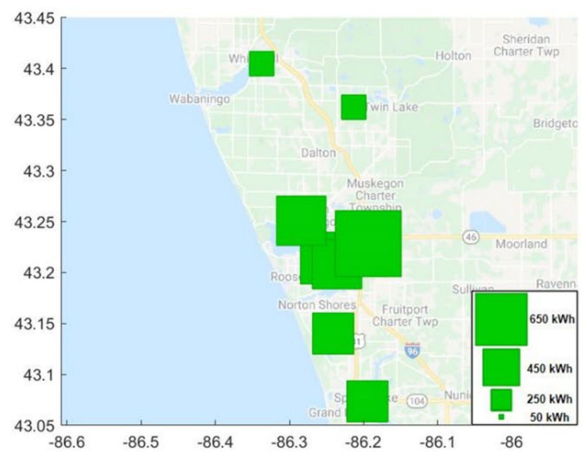


(ii) SLB size (kWh)

b) EV load factor=1.5



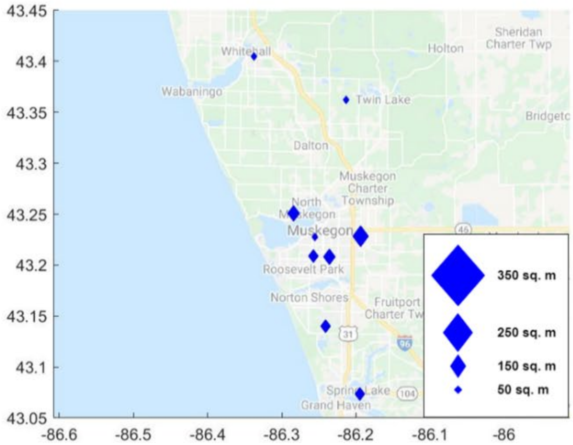
(i) Solar panel area (sq.m)



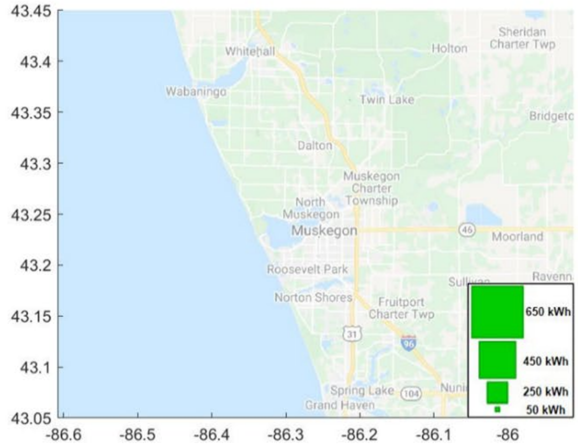
(ii) SLB size (kWh)

c) EV load factor=2

Figure 25 Size of SLB (6 hour storage duration) and solar panels for the city of Muskegon

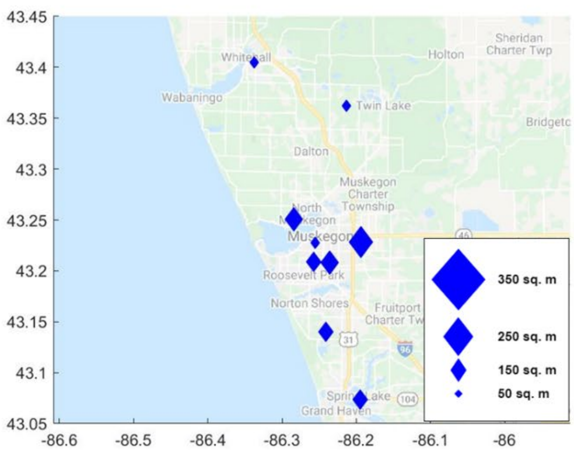


(i) Solar panel area (sq.m)

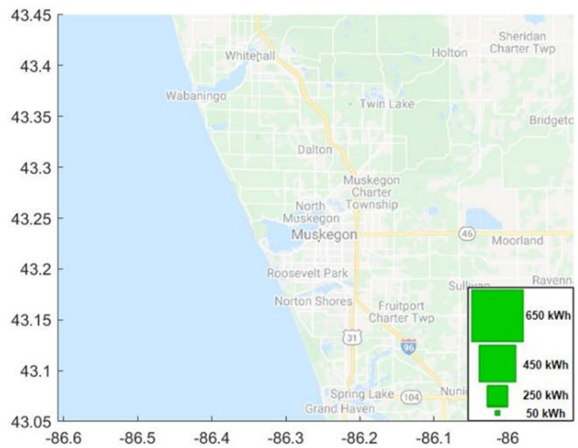


(ii) NB size (kWh)

a) EV load factor=1

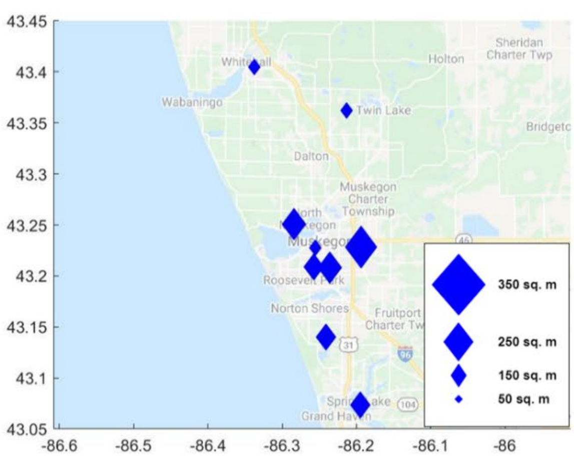


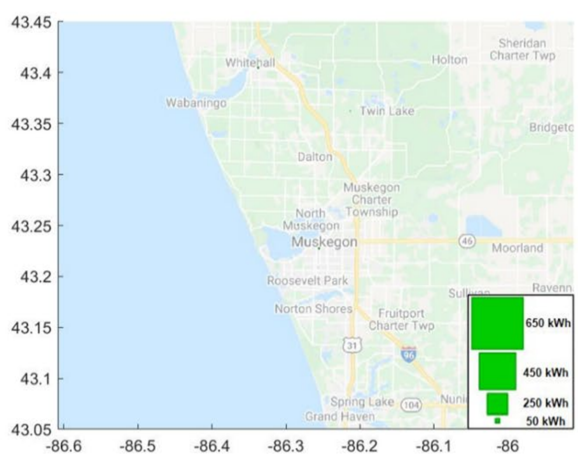
(i) Solar panel area (sq.m)



(ii) NB size (kWh)

b) EV load factor=1.5

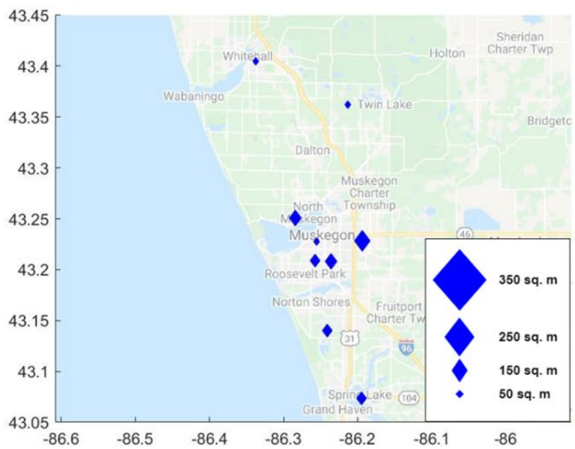




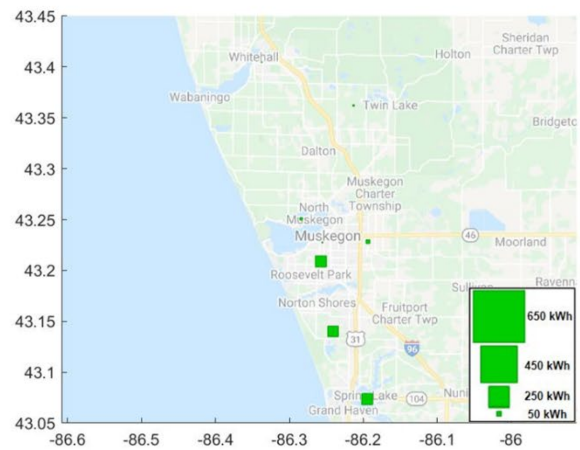
(i) Solar panel area (sq.m) (ii) NB size (kWh)

c) EV load factor=2

Figure 26 Size of NB (2 hour storage duration) and solar panels for the city of Muskegon

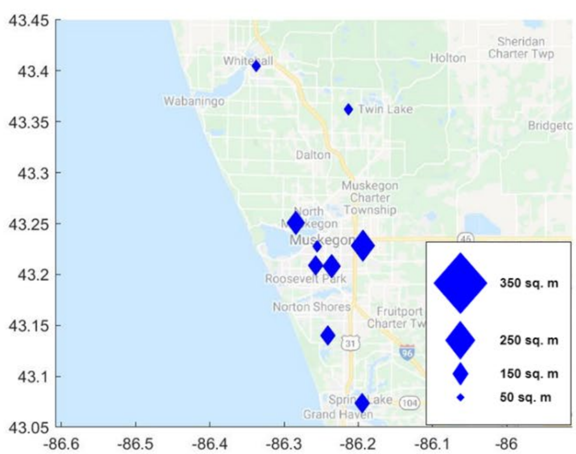


(i) Solar panel area (sq.m)

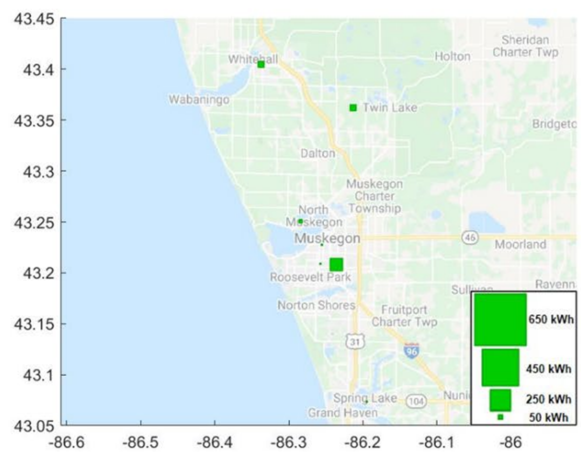


(ii) SLB size (kWh)

a) EV load factor=1

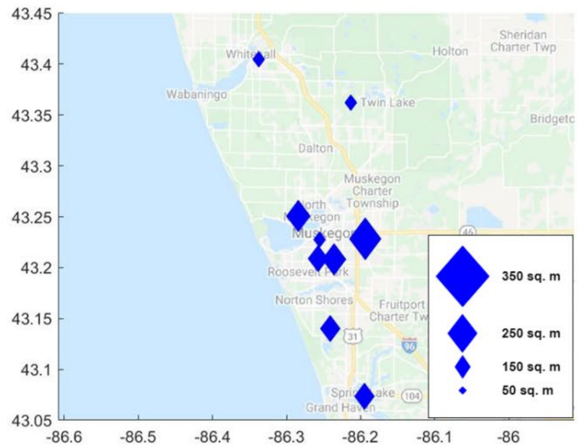


(i) Solar panel area (sq.m)

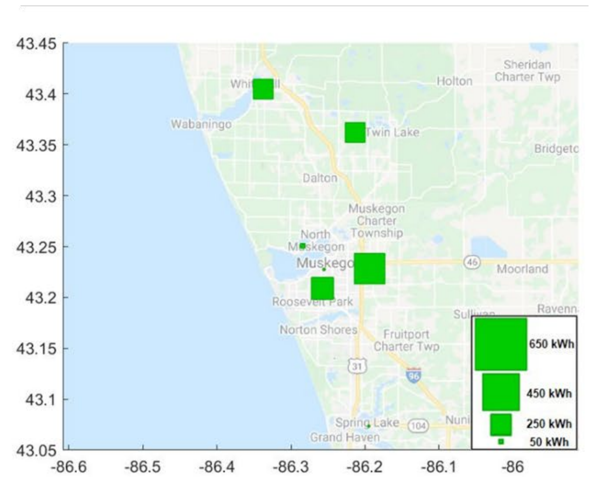


(ii) SLB size (kWh)

b) EV load factor=1.5



(i) Solar panel area (sq.m)

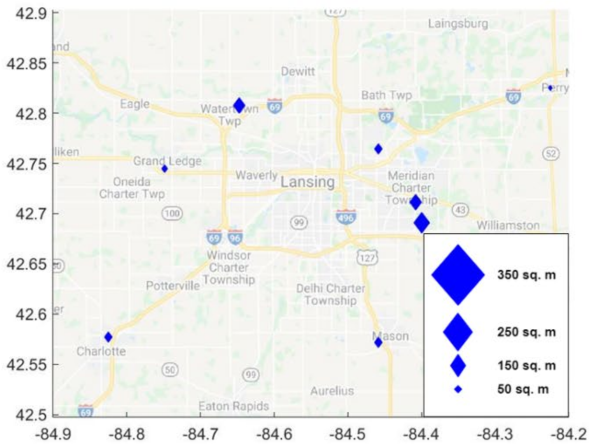


(ii) SLB size (kWh)

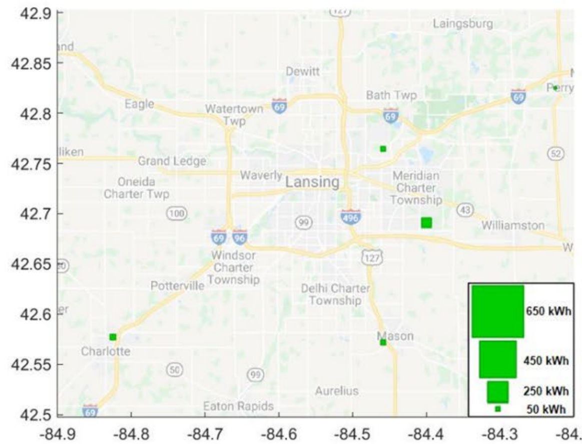
c) EV load factor=2

Figure 27 Size of SLB (2 hour storage duration) and solar panels for the city of Muskegon

Lansing

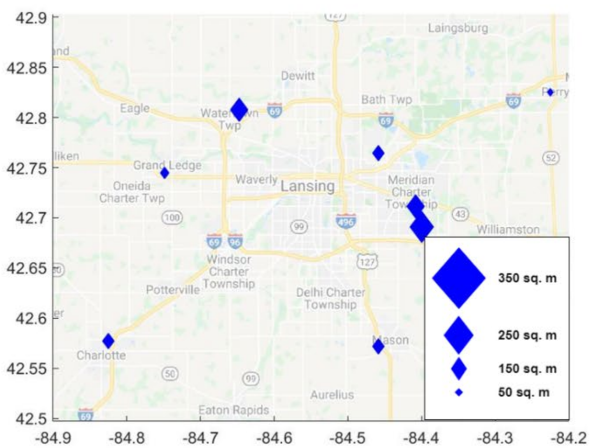


(i) Solar panel area (sq.m)

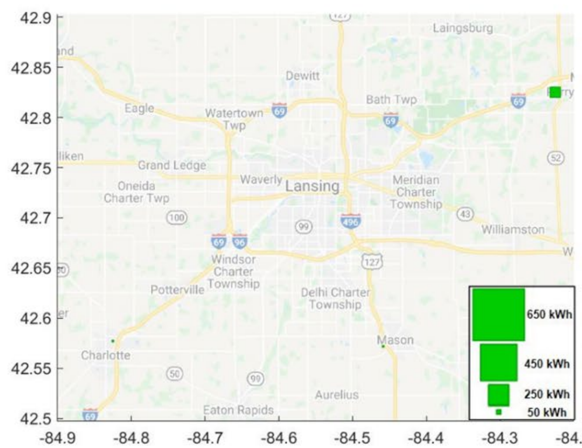


(ii) NB size (kWh)

a) EV load factor=1

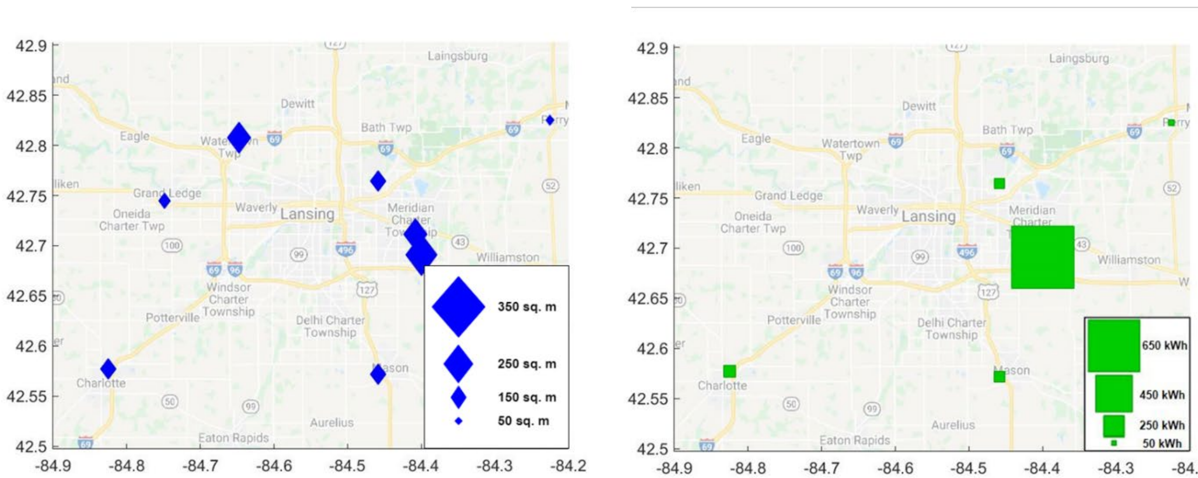


(i) Solar panel area (sq.m)



(ii) NB size (kWh)

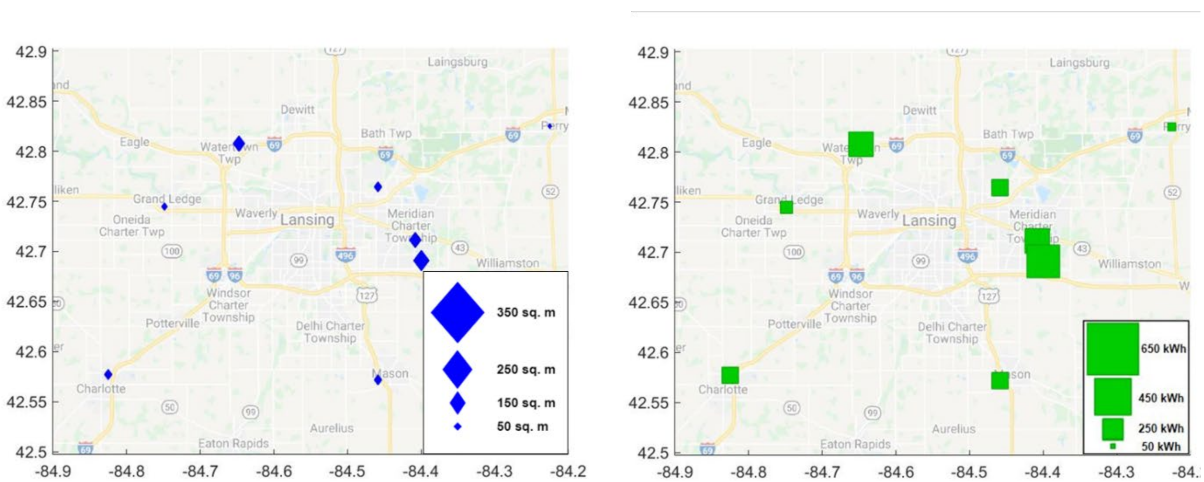
b) EV load factor=1.5



(i) Solar panel area (sq.m) (ii) NB size (kWh)

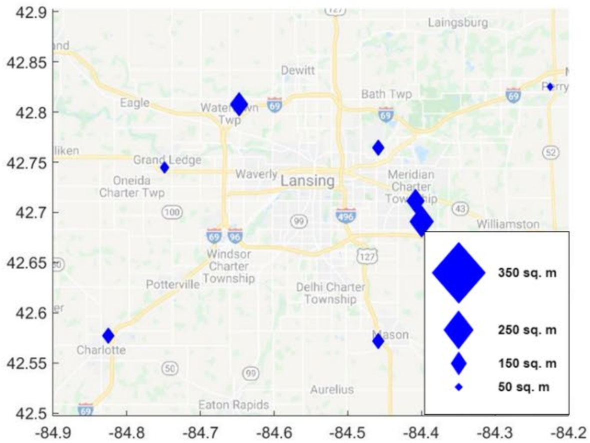
c) EV load factor=2

Figure 28 Size of NB (6 hour storage duration) and solar panels for the city of Lansing

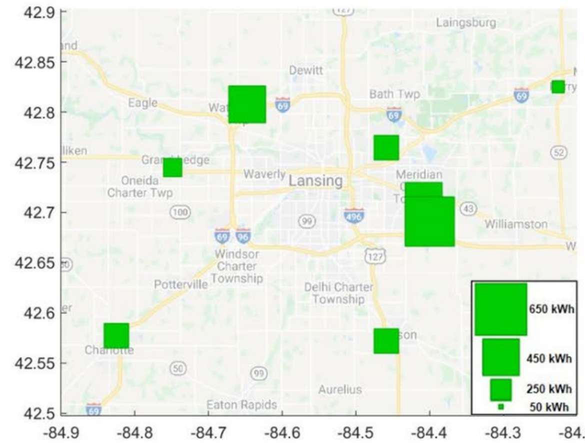


(i) Solar panel area (sq.m) (ii) SLB size (kWh)

a) EV load factor=1

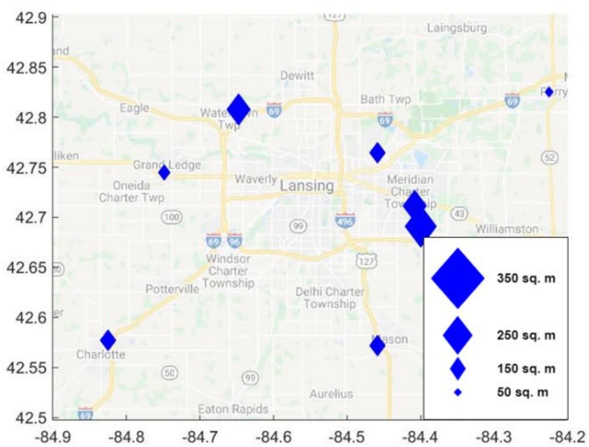


(i) Solar panel area (sq.m)

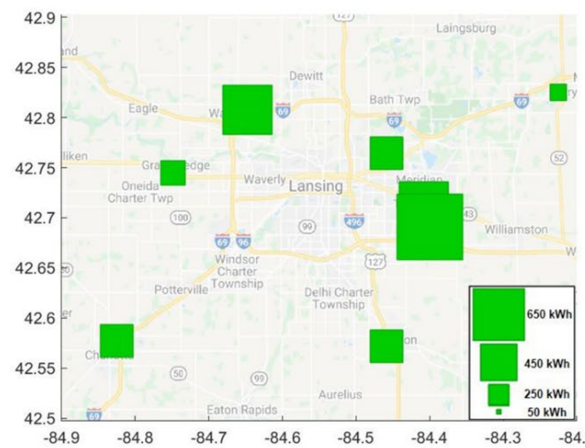


(ii) SLB size (kWh)

b) EV load factor=1.5



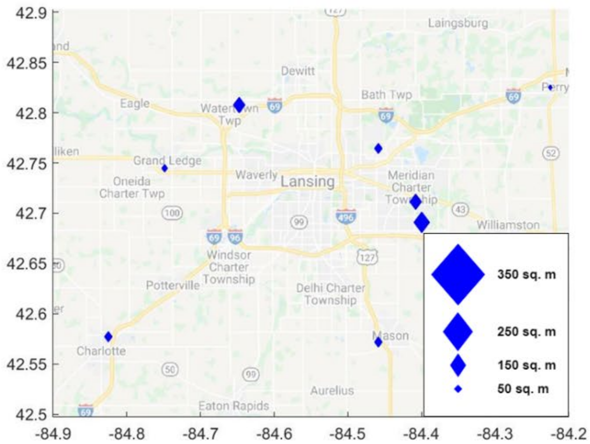
(i) Solar panel area (sq.m)



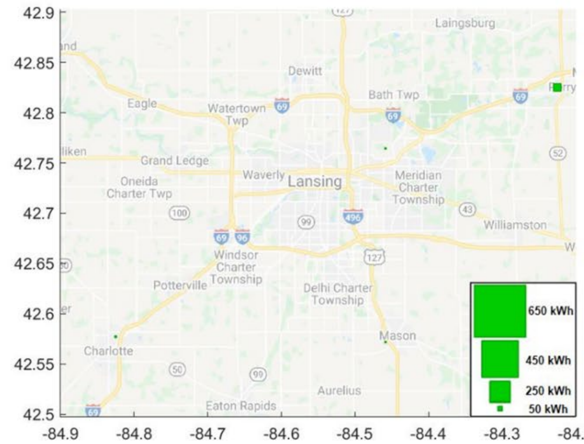
(ii) SLB size (kWh)

c) EV load factor=2

Figure 29 Size of SLB (6 hour storage duration) and solar panels for the city of Lansing

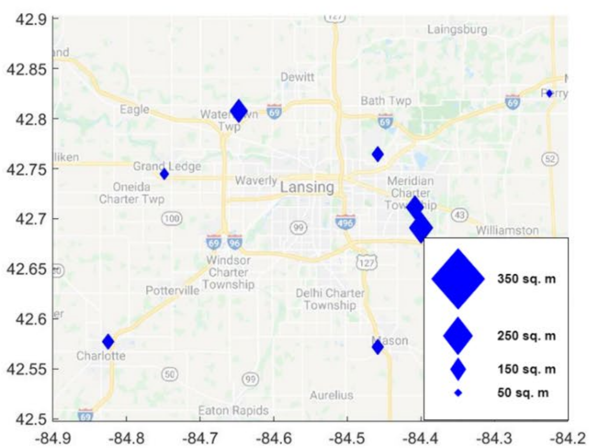


(i) Solar panel area (sq.m)

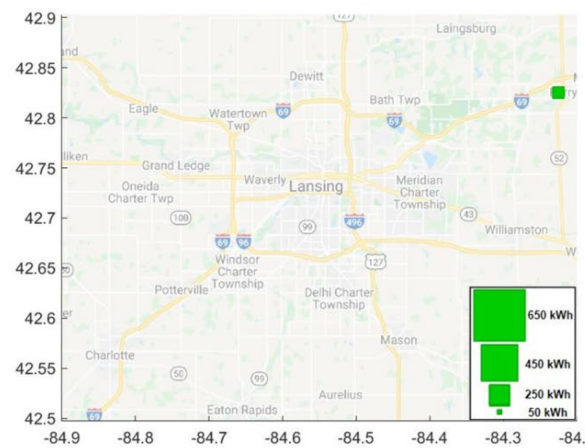


(ii) NB size (kWh)

a) EV load factor=1

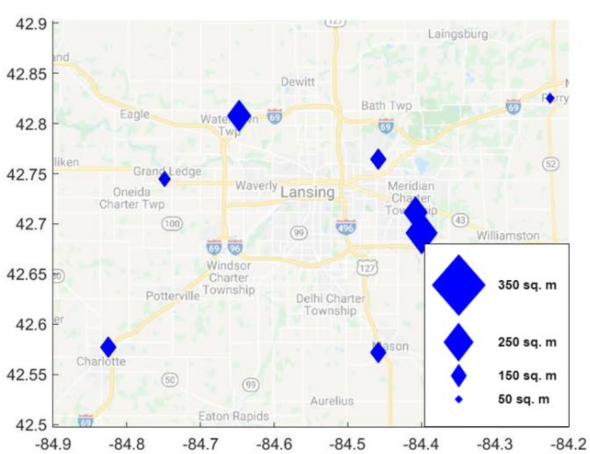


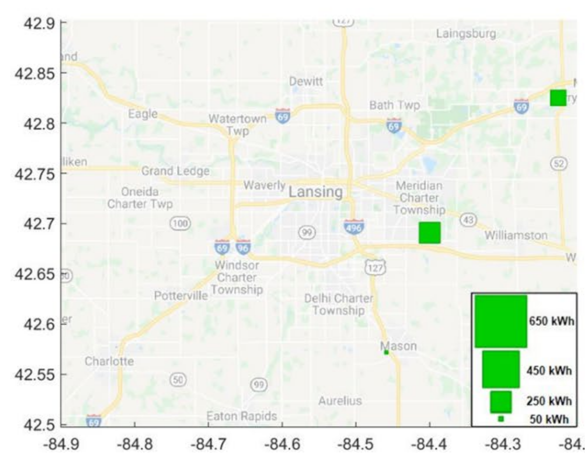
(i) Solar panel area (sq.m)



(ii) NB size (kWh)

b) EV load factor=1.5

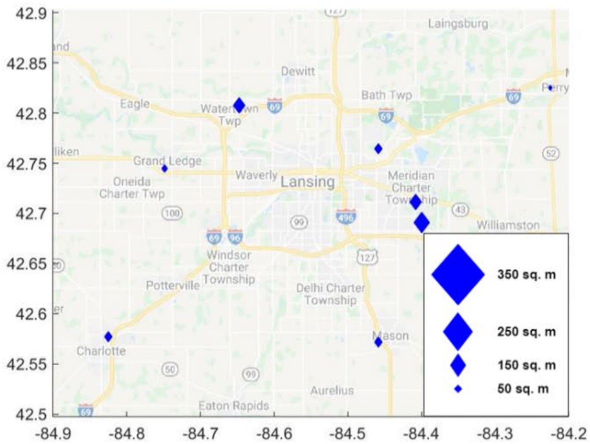


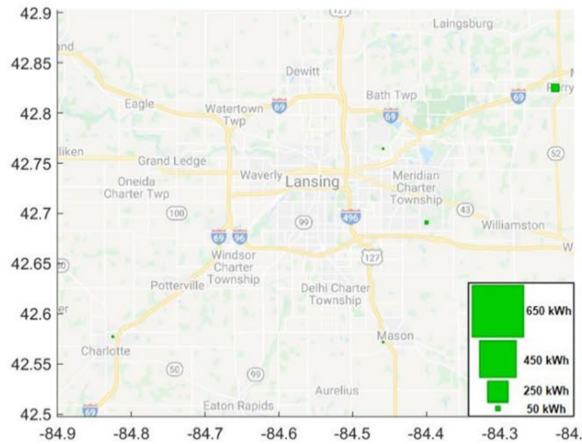


(i) Solar panel area (sq.m) (ii) NB size (kWh)

c) EV load factor=2

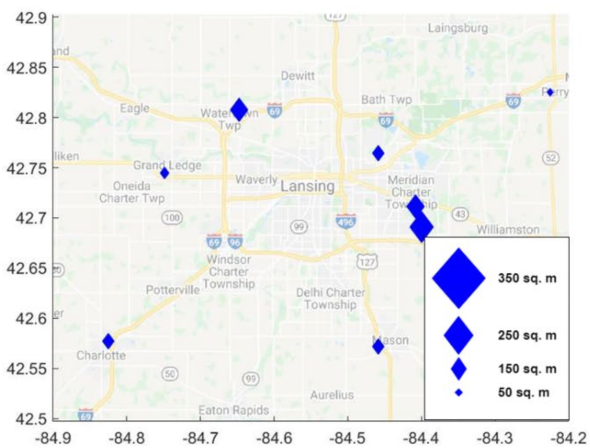
Figure 30 Size of NB (2 hour storage duration) and solar panels for the city of Lansing

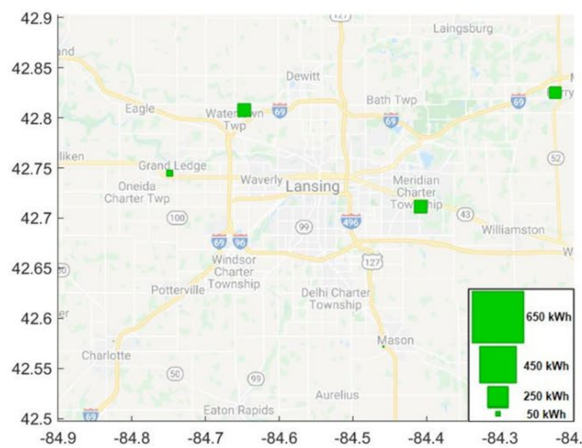




(i) Solar panel area (sq.m) (ii) SLB size (kWh)

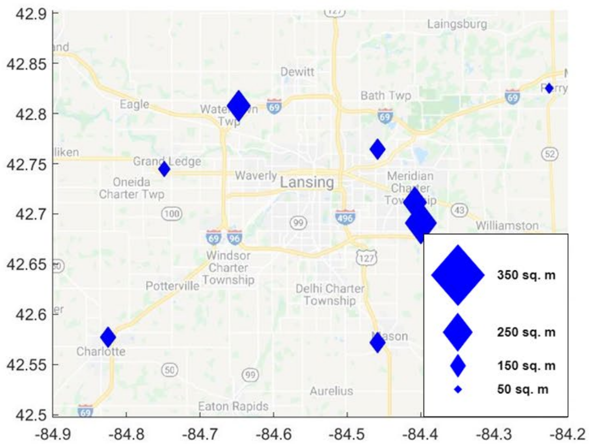
a) EV load factor=1



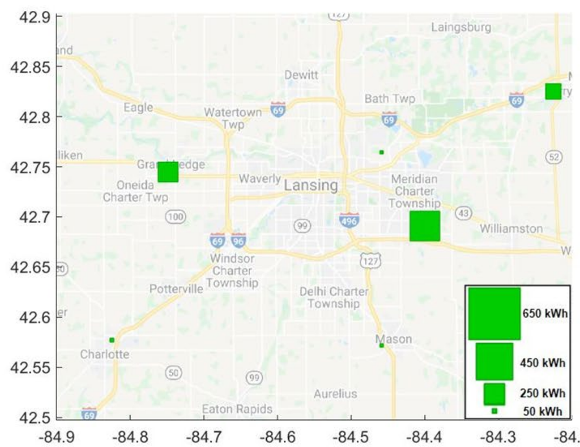


(i) Solar panel area (sq.m) (ii) SLB size (kWh)

b) EV load factor=1.5



(i) Solar panel area (sq.m)

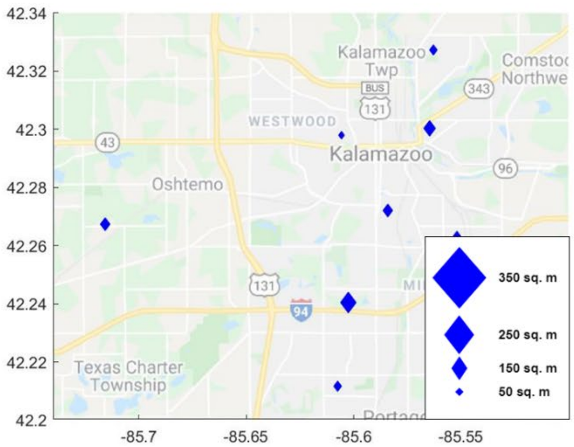


(ii) SLB size (kWh)

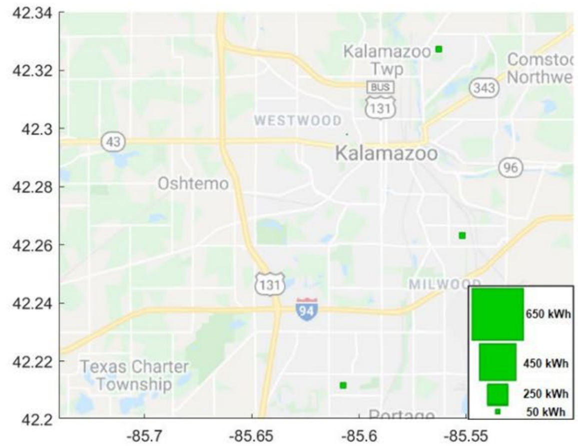
c) EV load factor=2

Figure 31 Size of SLB (2 hour storage duration) and solar panels for the city of Lansing

Kalamazoo

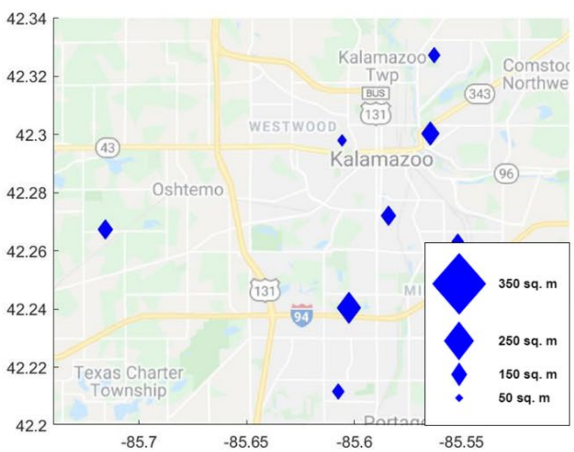


(i) Solar panel area (sq.m)

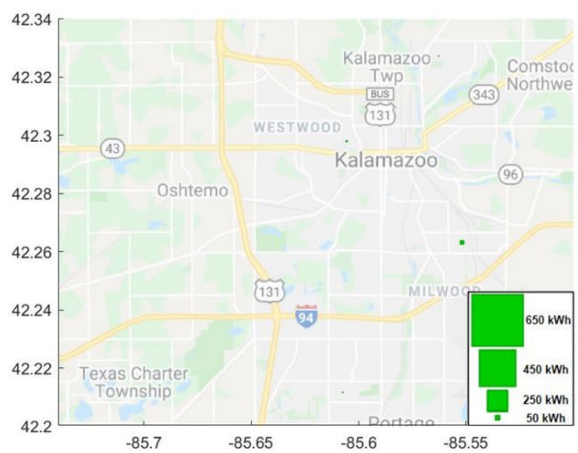


(ii) NB size (kWh)

a) EV load factor=1

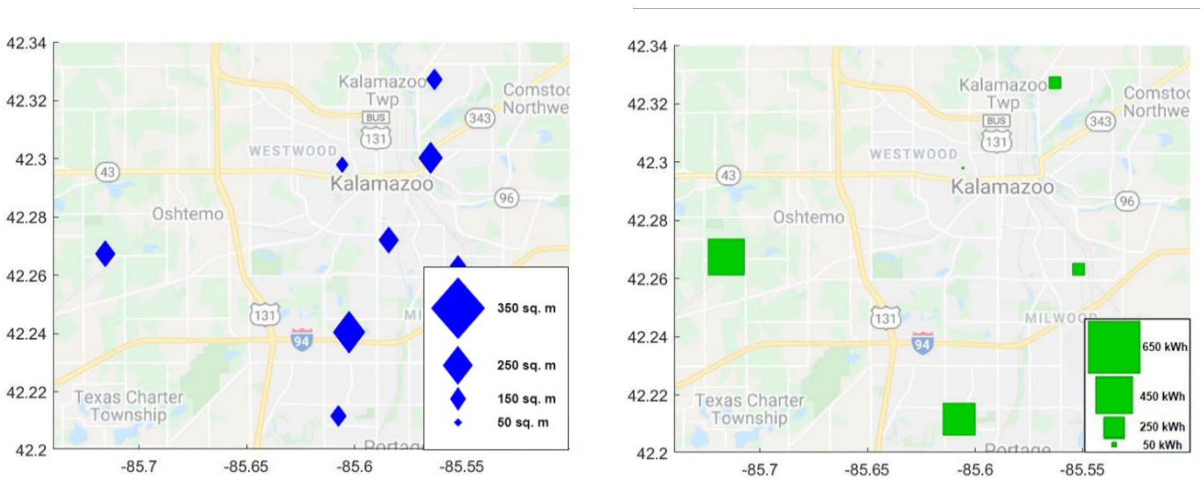


(i) Solar panel area (sq.m)



(ii) NB size (kWh)

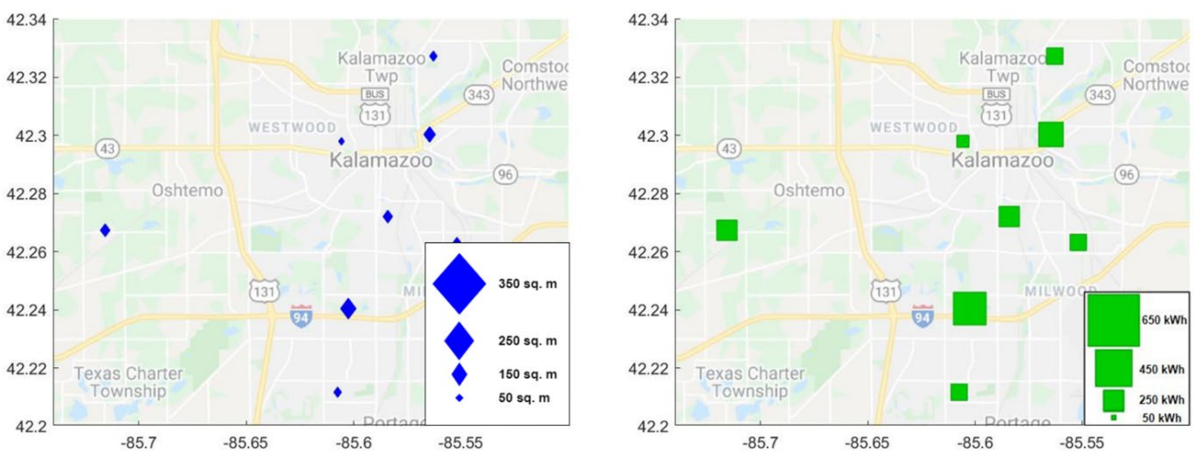
b) EV load factor=1.5



(i) Solar panel area (sq.m) (ii) NB size (kWh)

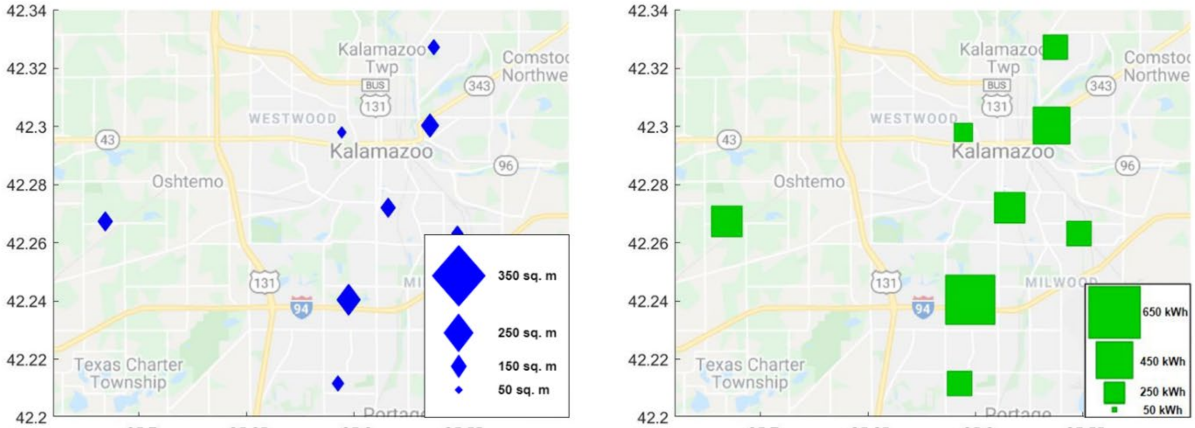
c) EV load factor=2

Figure 32 Size of NB (6 hour storage duration) and solar panels for the city of Kalamazoo



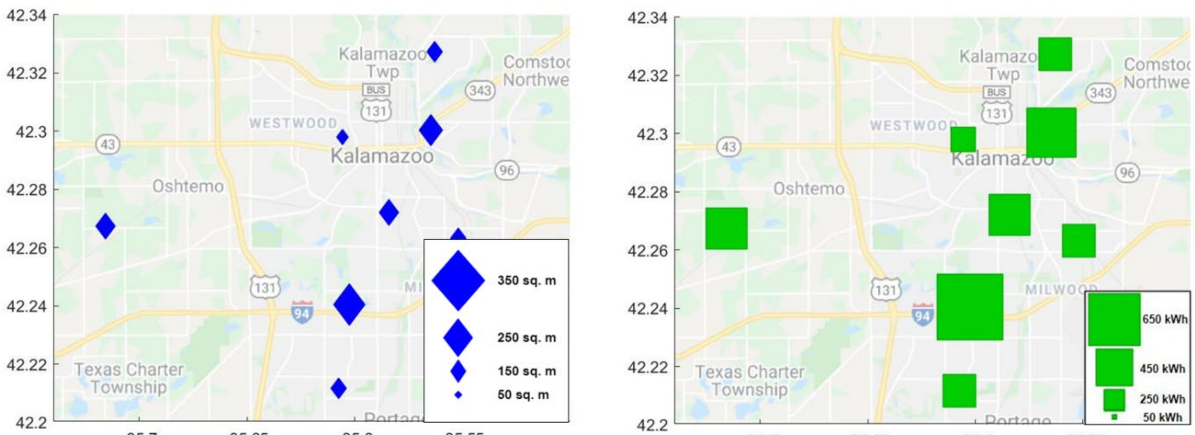
(i) Solar panel area (sq.m) (ii) SLB size (kWh)

a) EV load factor=1



(i) Solar panel area (sq.m) (ii) SLB size (kWh)

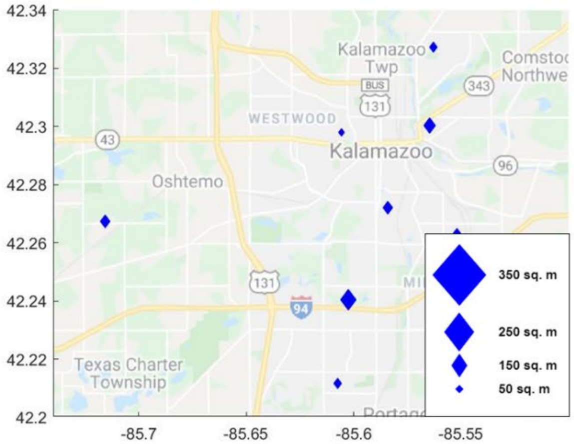
b) EV load factor=1.5



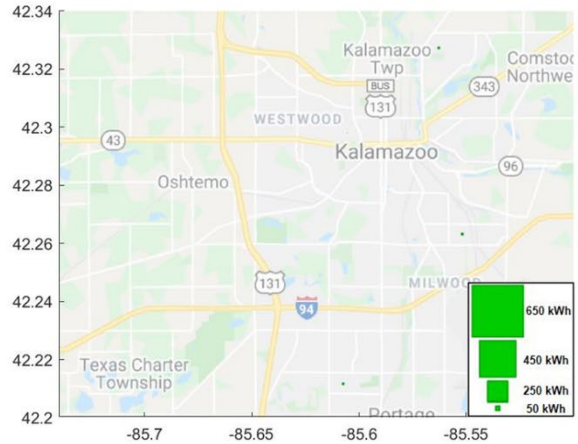
(i) Solar panel area (sq.m) (ii) SLB size (kWh)

c) EV load factor=2

Figure 33 Size of SLB (6 hour storage duration) and solar panels for the city of Kalamazoo

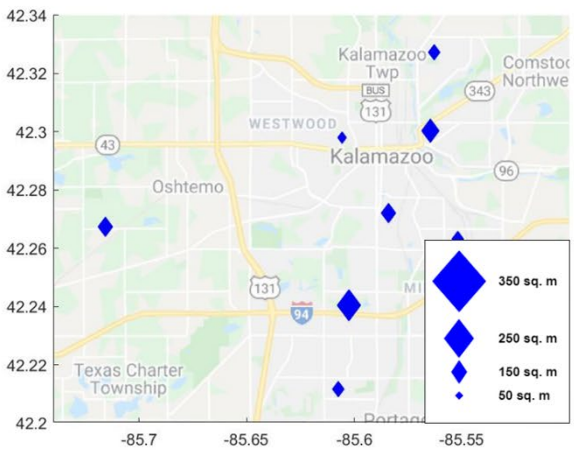


(i) Solar panel area (sq.m)

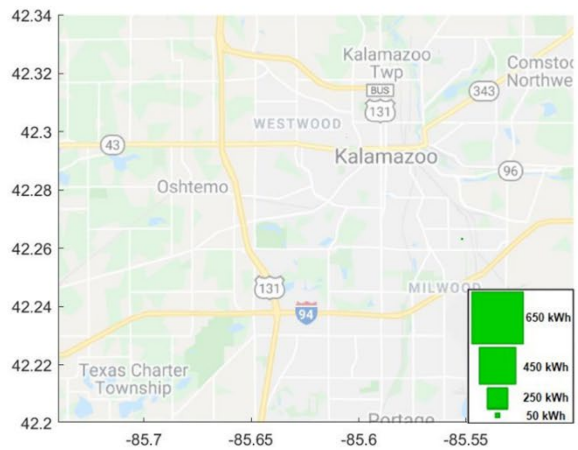


(ii) NB size (kWh)

a) EV load factor=1

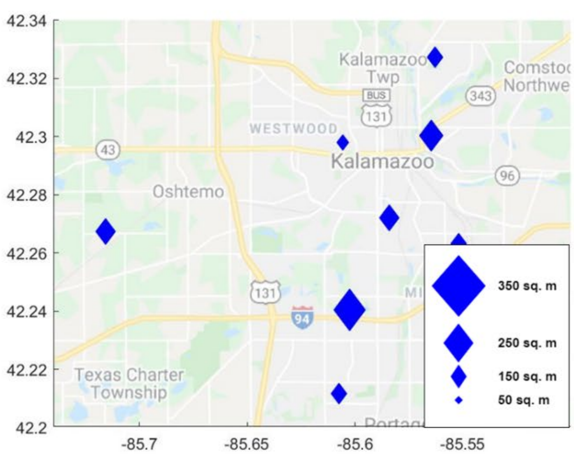


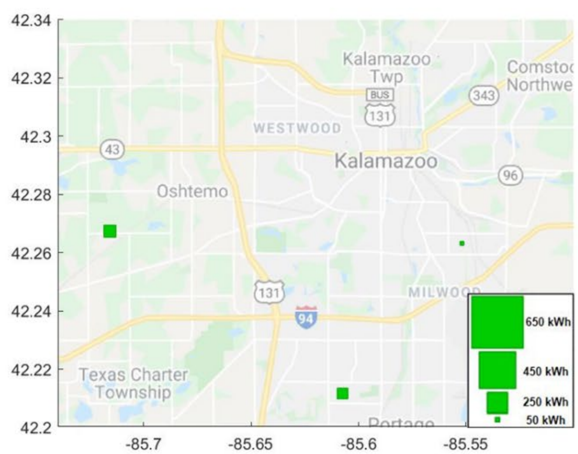
(i) Solar panel area (sq.m)



(ii) NB size (kWh)

b) EV load factor=1.5

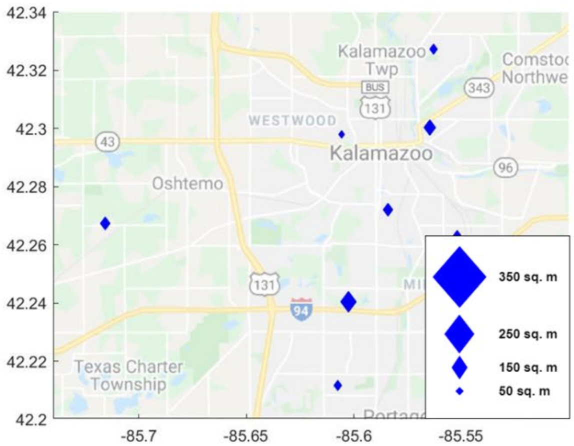




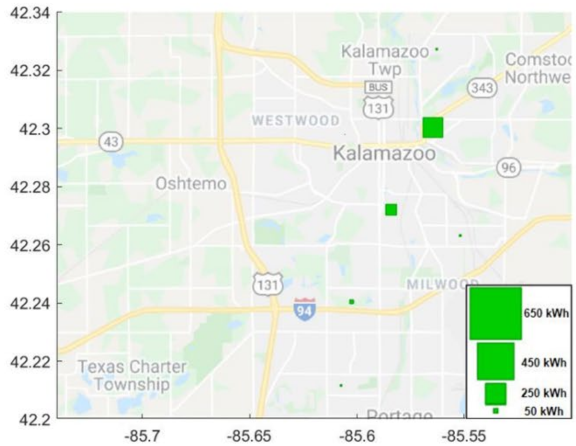
(i) Solar panel area (sq.m) (ii) NB size (kWh)

c) EV load factor=2

Figure 34 Size of NB (2 hour storage duration) and solar panels for the city of Kalamazoo

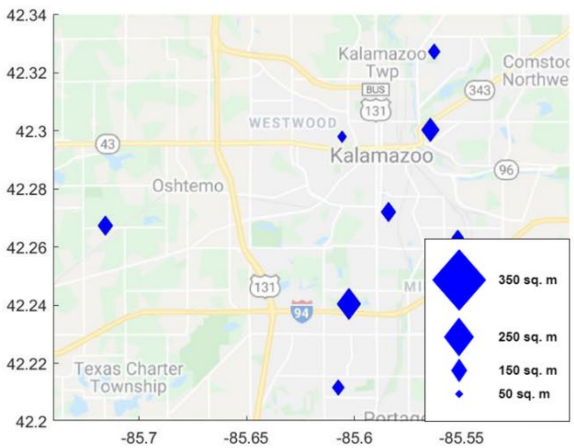


(i) Solar panel area (sq.m)

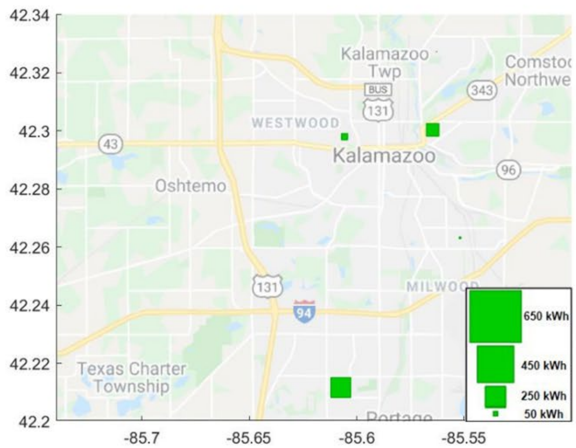


(ii) SLB size (kWh)

a) EV load factor=1

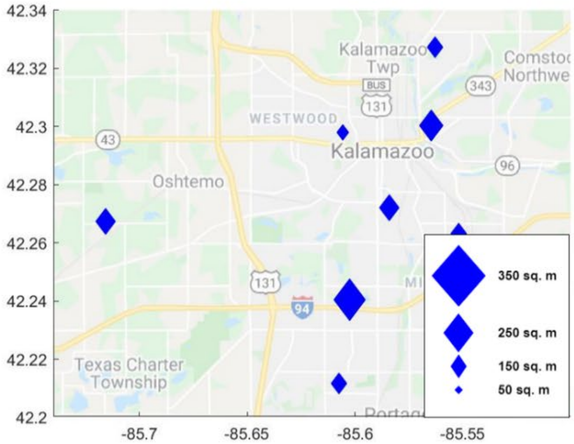


(i) Solar panel area (sq.m)

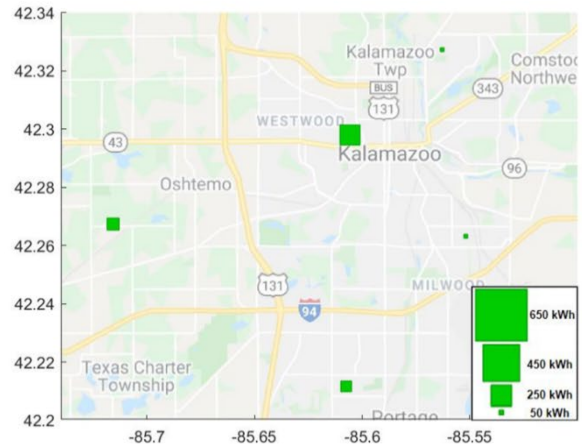


(ii) SLB size (kWh)

b) EV load factor=1.5



(i) Solar panel area (sq.m)

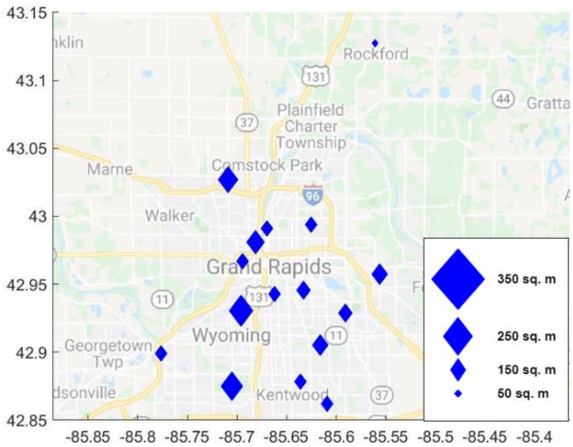


(ii) SLB size (kWh)

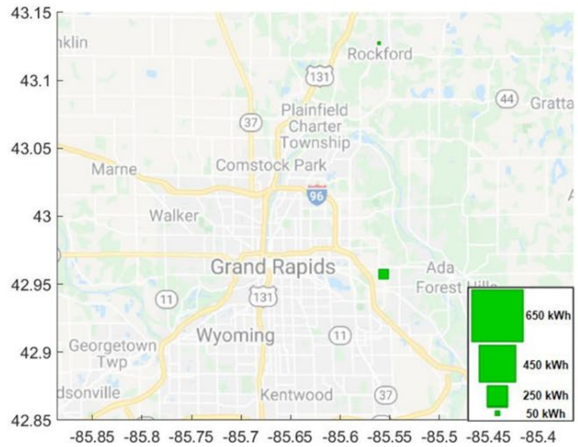
c) EV load factor=2

Figure 35 Size of SLB (2 hour storage duration) and solar panels for the city of Kalamazoo

Grand Rapids

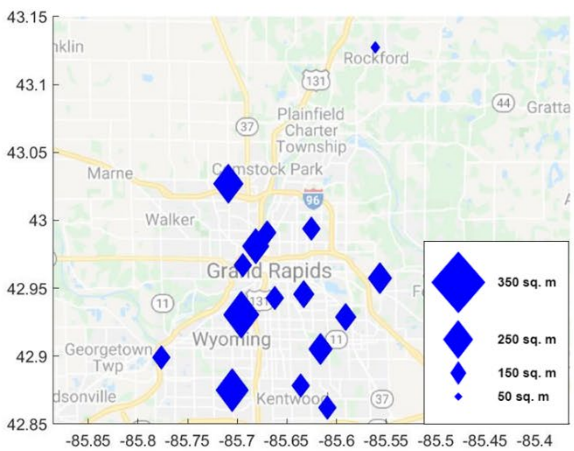


(i) Solar panel area (sq.m)

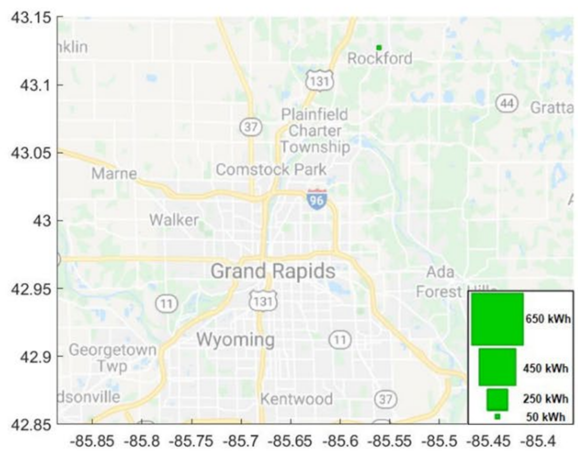


(ii) NB size (kWh)

a) EV load factor=1

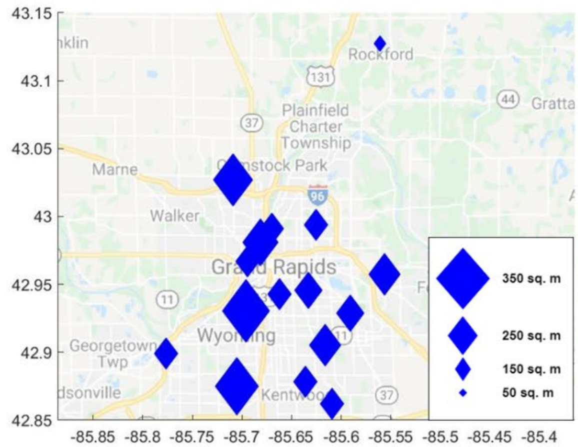


(i) Solar panel area (sq.m)

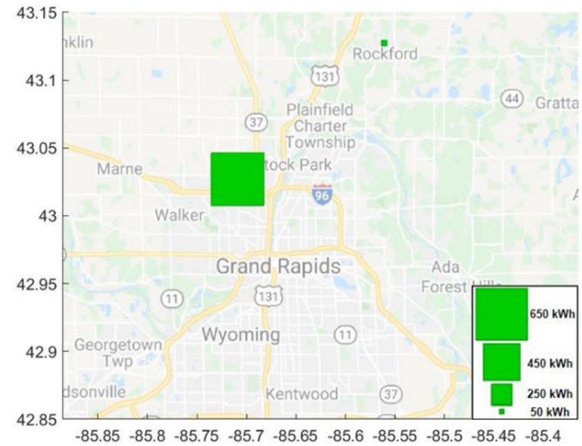


(ii) NB size (kWh)

b) EV load factor=1.5



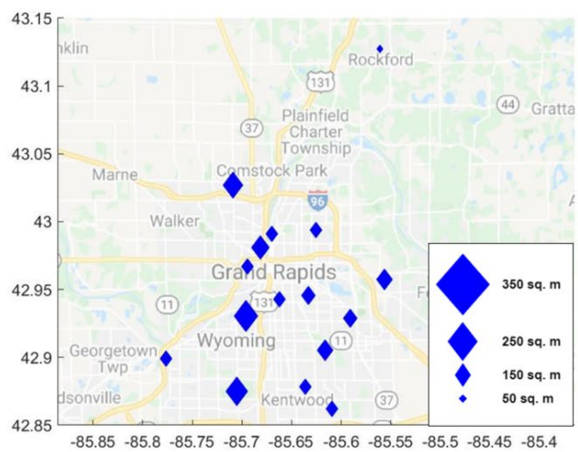
(i) Solar panel area (sq.m)



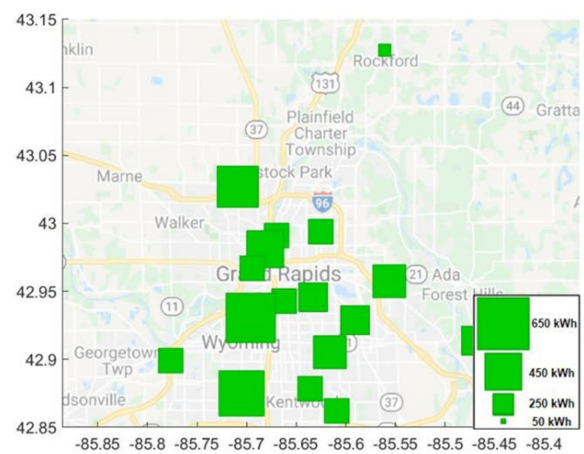
(ii) NB size (kWh)

c) EV load factor=2

Figure 36 Size of NB (6 hour storage duration) and solar panels for the city of Grand Rapids

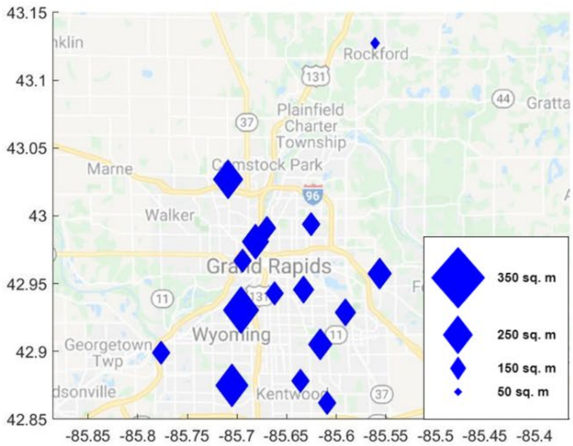


(i) Solar panel area (sq.m)

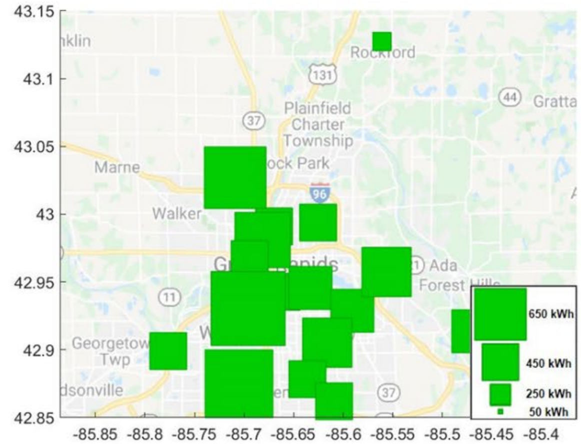


(ii) SLB size (kWh)

a) EV load factor=1

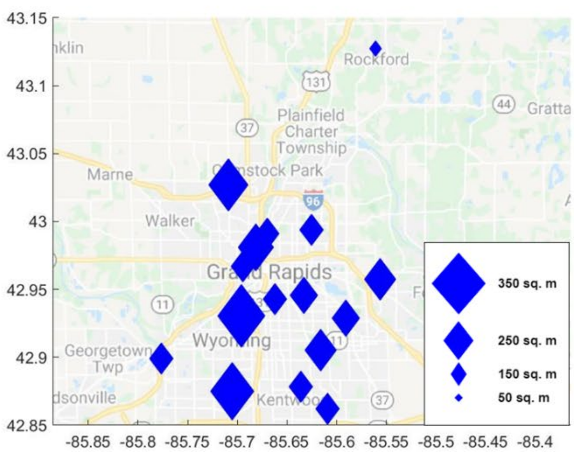


(i) Solar panel area (sq.m)

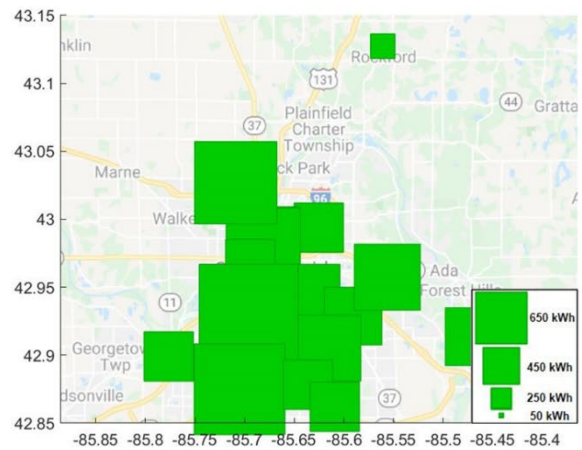


(ii) SLB size (kWh)

b) EV load factor=1.5



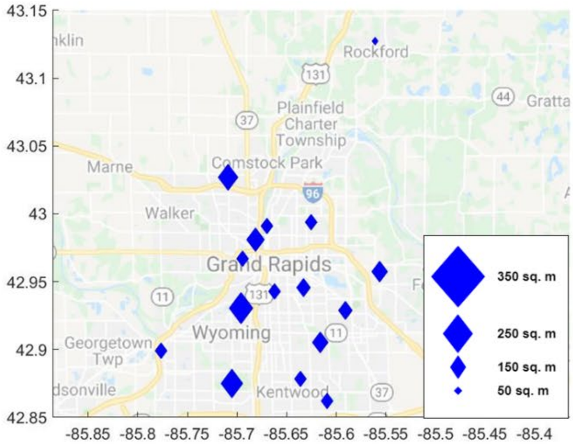
(i) Solar panel area (sq.m)



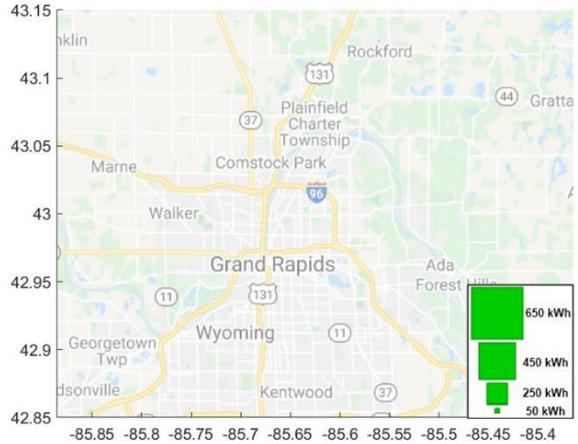
(ii) SLB size (kWh)

c) EV load factor=2

Figure 37 Size of SLB (6 hour storage duration) and solar panels for the city of Grand Rapids

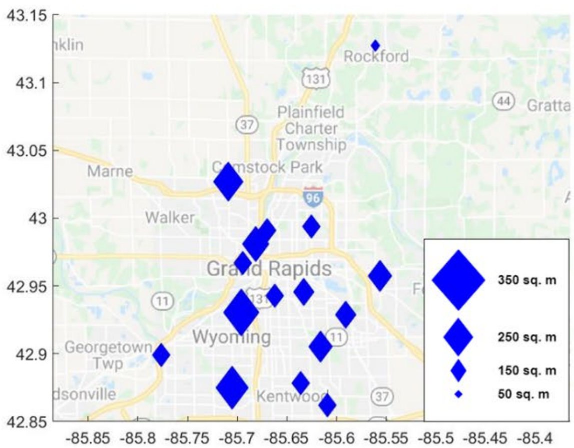


(i) Solar panel area (sq.m)

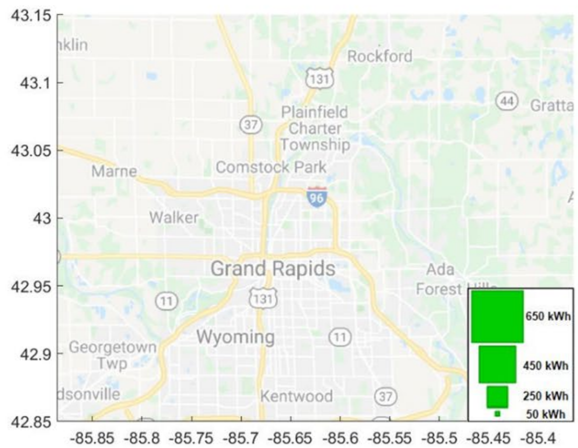


(ii) NB size (kWh)

a) EV load factor=1

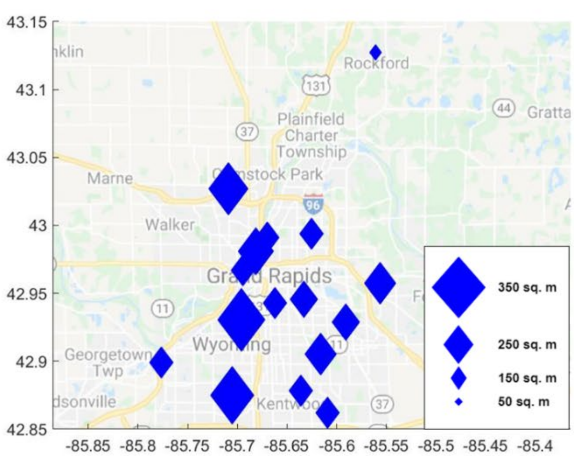


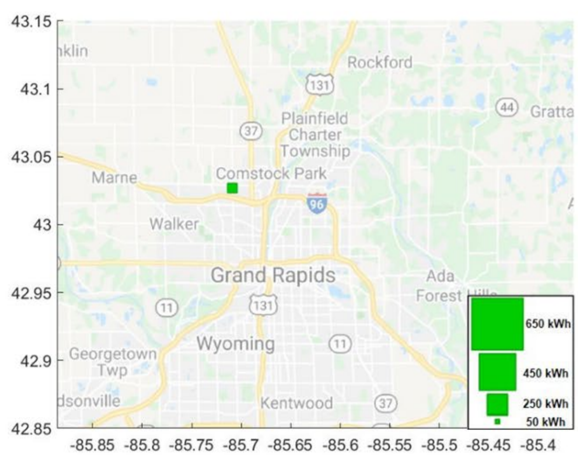
(i) Solar panel area (sq.m)



(ii) NB size (kWh)

b) EV load factor=1.5

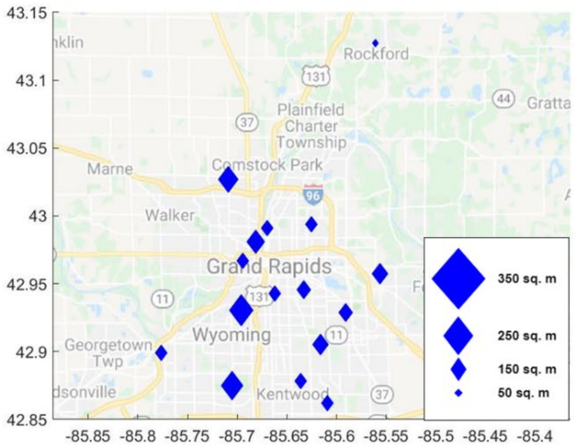




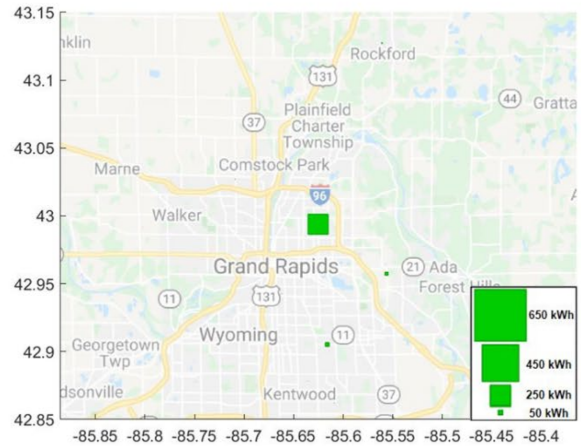
(i) Solar panel area (sq.m) (ii) NB size (kWh)

c) EV load factor=2

Figure 38 Size of NB (2 hour storage duration) and solar panels for the city of Grand Rapids

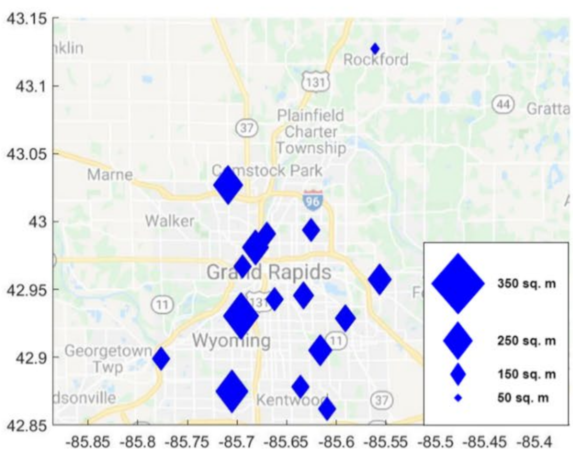


(i) Solar panel area (sq.m)

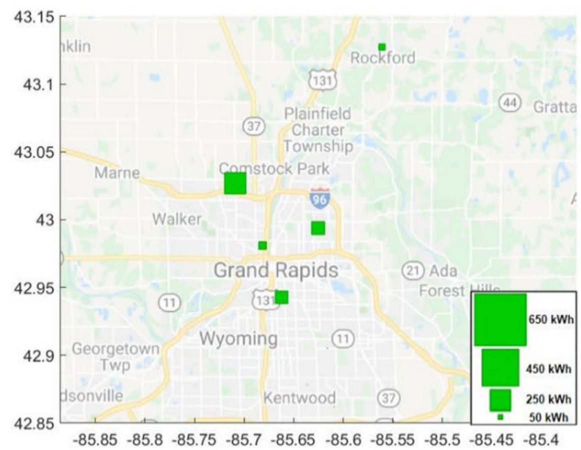


(ii) SLB size (kWh)

a) EV load factor=1

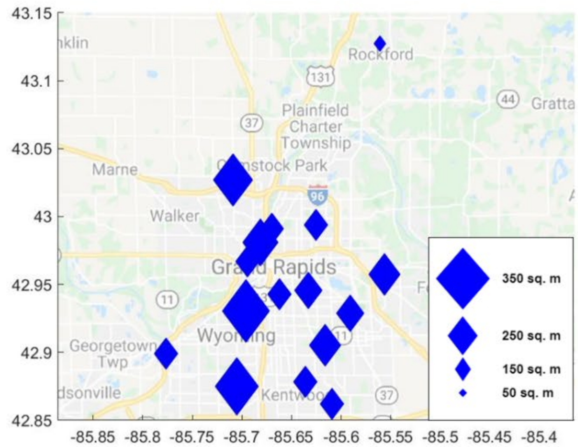


(i) Solar panel area (sq.m)

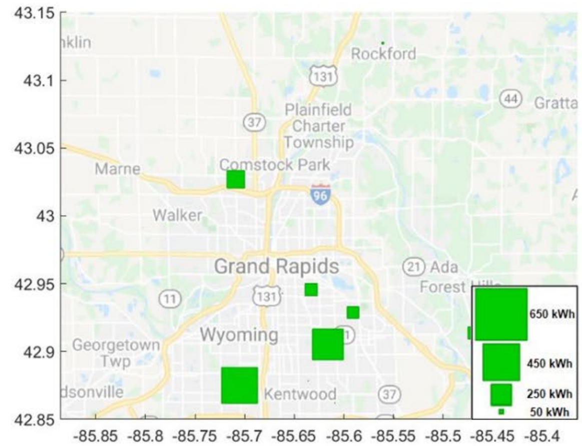


(ii) SLB size (kWh)

b) EV load factor=1.5



(i) Solar panel area (sq.m)

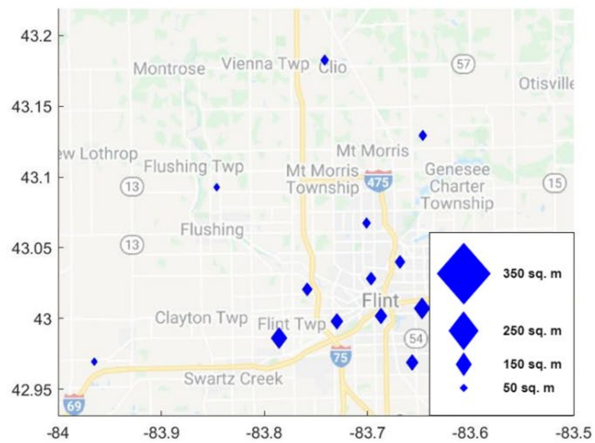


(ii) SLB size (kWh)

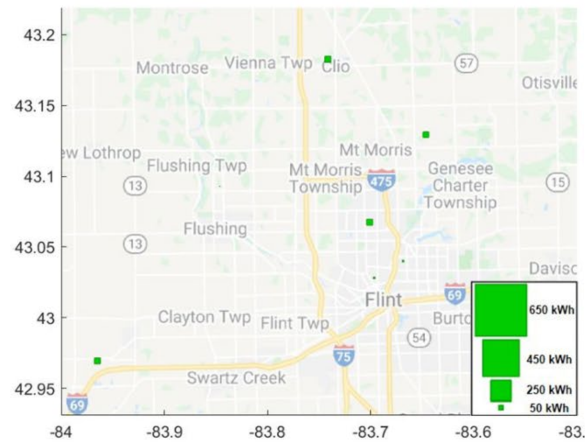
c) EV load factor=2

Figure 39 Size of SLB (2 hour storage duration) and solar panels for the city of Grand Rapids

Flint

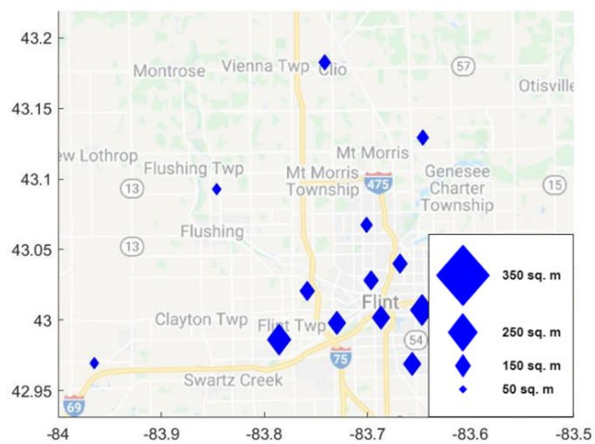


(i) Solar panel area (sq.m)

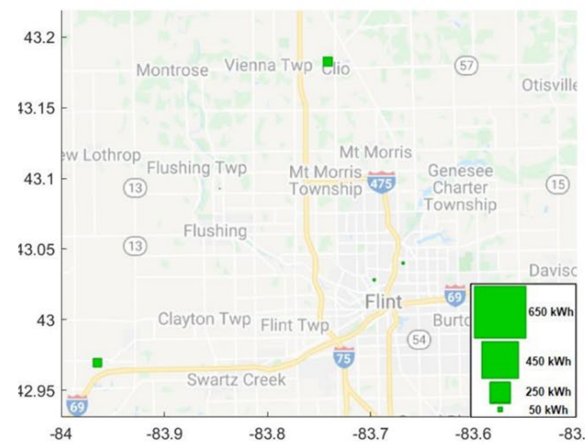


(ii) NB size (kWh)

a) EV load factor=1

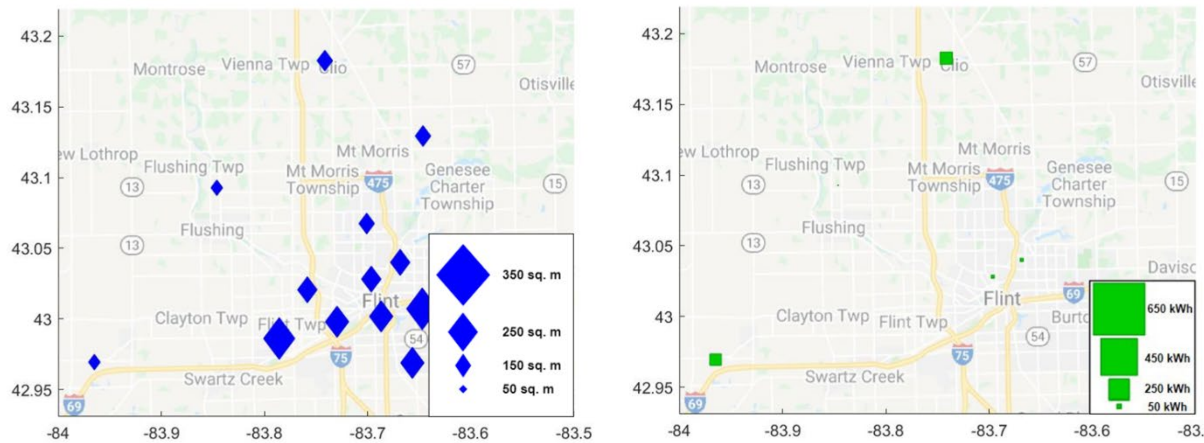


(i) Solar panel area (sq.m)



(ii) NB size (kWh)

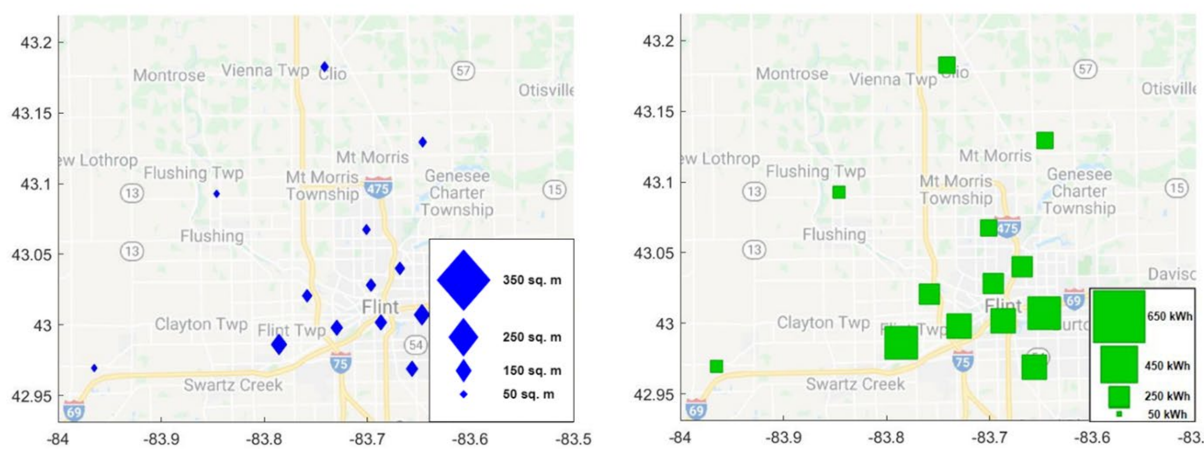
b) EV load factor=1.5



(i) Solar panel area (sq.m) (ii) NB size (kWh)

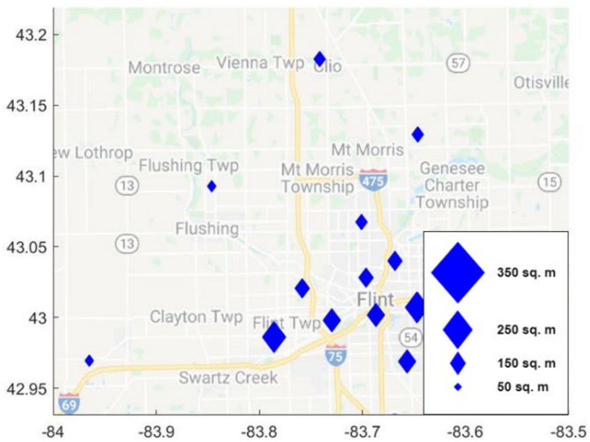
c) EV load factor=2

Figure 40 Size of NB (6 hour storage duration) and solar panels for the city of Flint

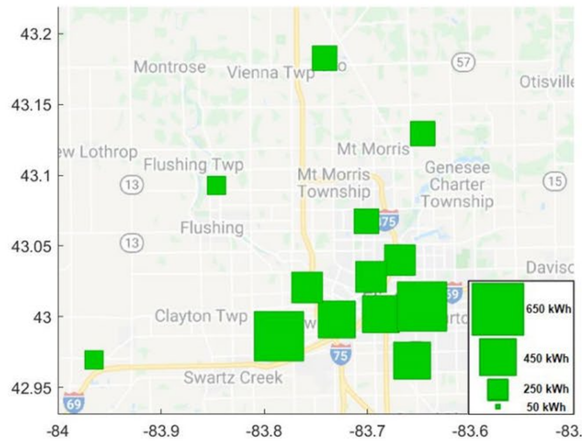


(i) Solar panel area (sq.m) (ii) SLB size (kWh)

a) EV load factor=1

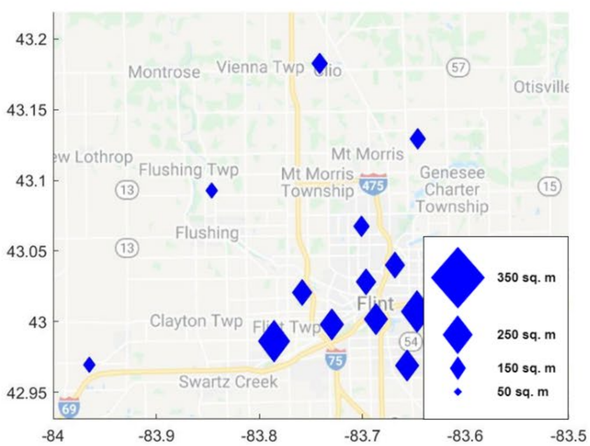


(i) Solar panel area (sq.m)

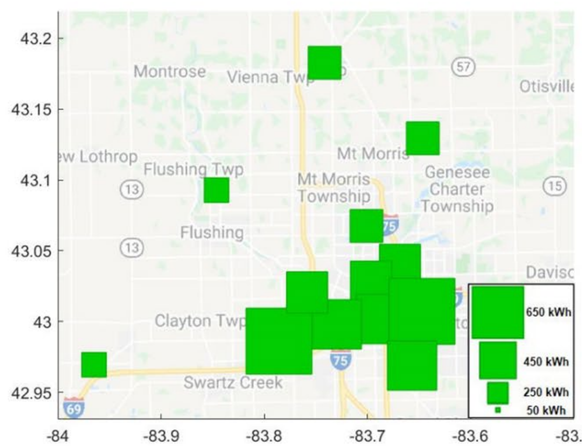


(ii) SLB size (kWh)

b) EV load factor=1.5



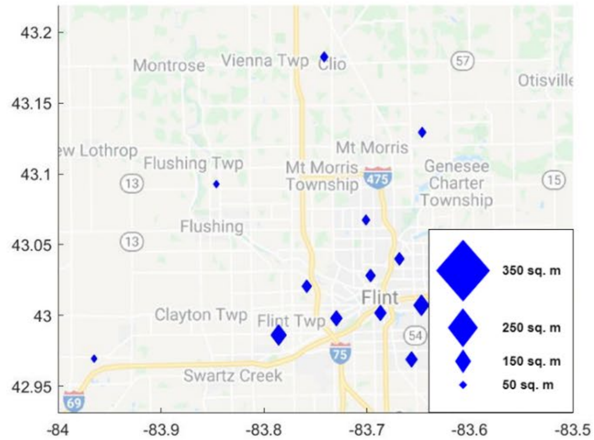
(i) Solar panel area (sq.m)



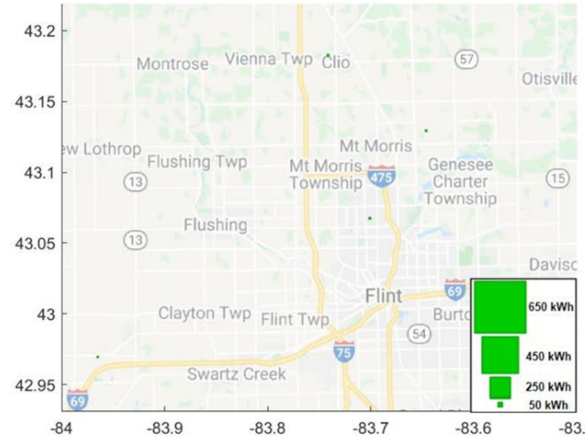
(ii) SLB size (kWh)

c) EV load factor=2

Figure 41 Size of SLB (6 hour storage duration) and solar panels for the city of Flint

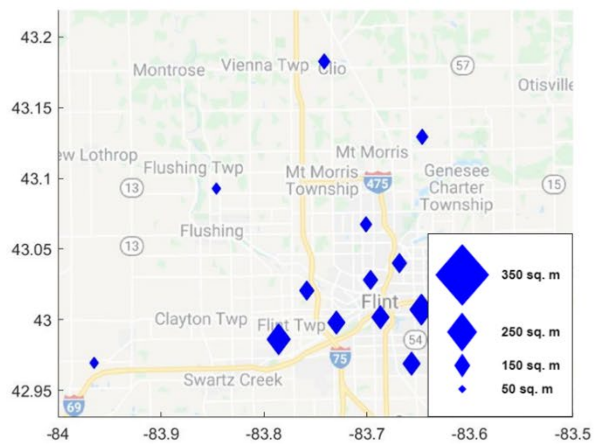


(i) Solar panel area (sq.m)

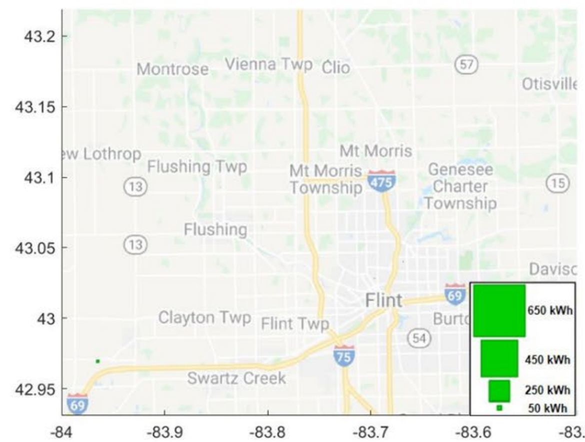


(ii) NB size (kWh)

a) EV load factor=1

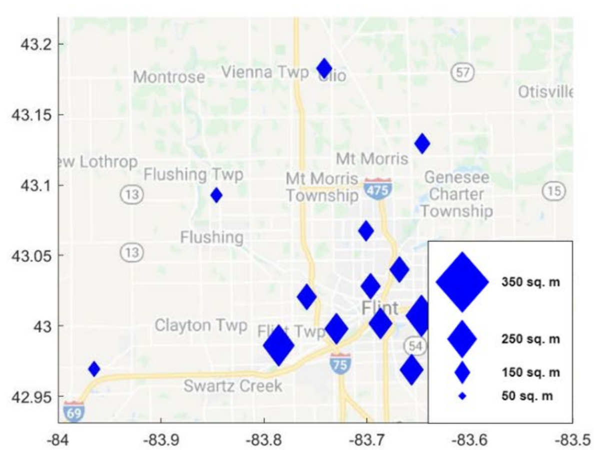


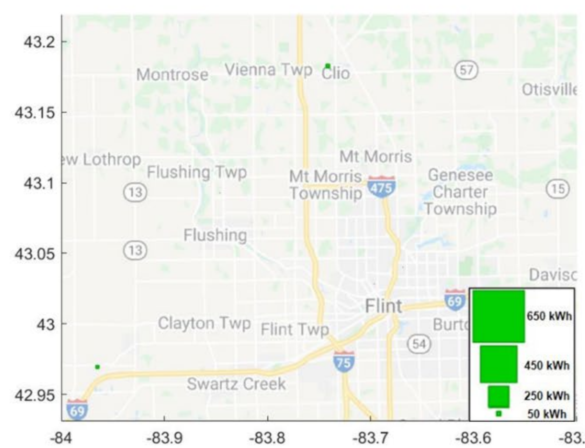
(i) Solar panel area (sq.m)



(ii) NB size (kWh)

b) EV load factor=1.5

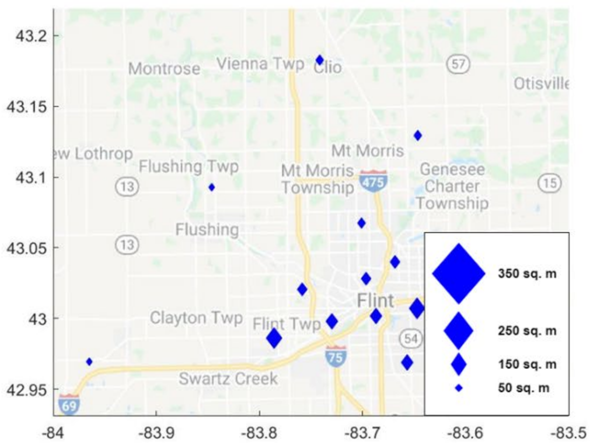




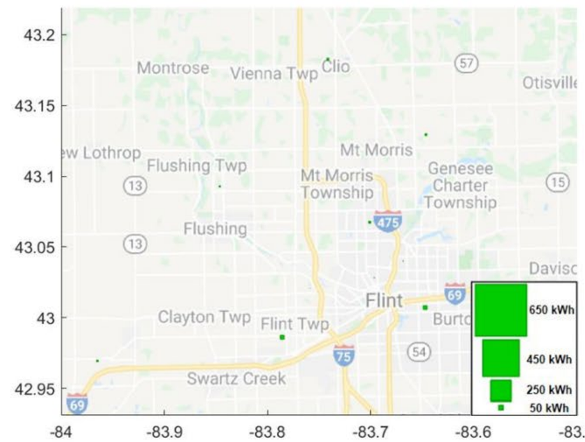
(i) Solar panel area (sq.m) (ii) NB size (kWh)

c) EV load factor=2

Figure 42 Size of NB (2 hour storage duration) and solar panels for the city of Flint

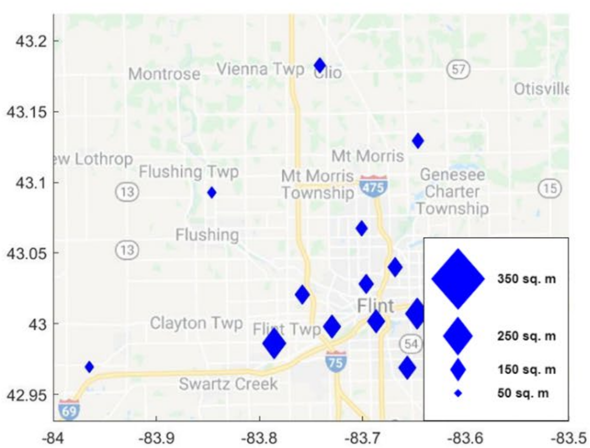


(i) Solar panel area (sq.m)

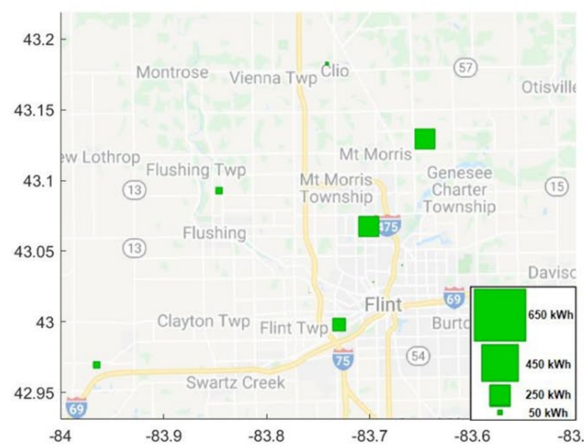


(ii) SLB size (kWh)

a) EV load factor=1

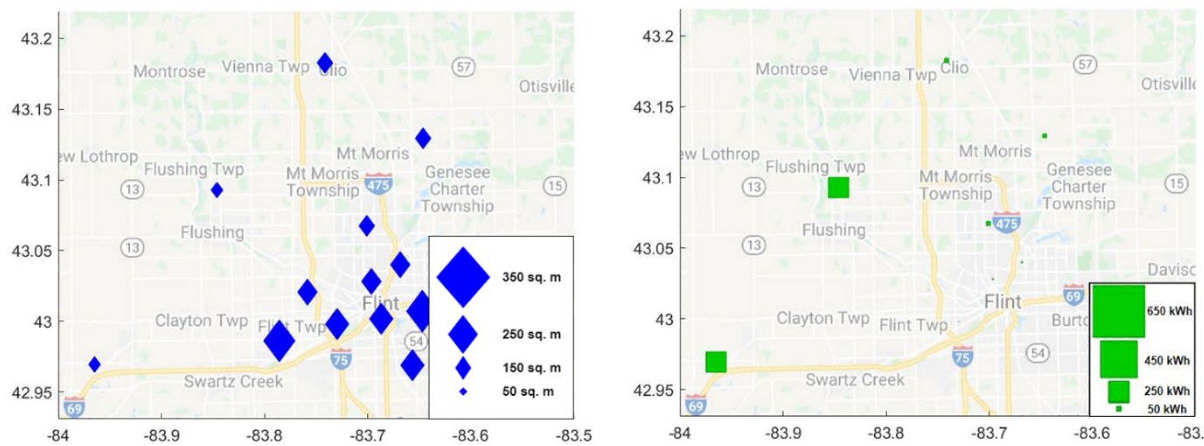


(i) Solar panel area (sq.m)



(ii) SLB size (kWh)

b) EV load factor=1.5



(i) Solar panel area (sq.m) (ii) SLB size (kWh)

c) EV load factor=2

Figure 43 Size of SLB (2 hour storage duration) and solar panels for the city of Flint

APPENDIX B: COST BREAKDOWN FOR 2-HOUR AND 6-HOUR STORAGE DURATION

BESS with 6 hour storage duration and solar panels

TABLE 7 Cost breakdown for the case of 6 hour NB and the solar panels in Michigan

Saginaw								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	721	71	207	0	1574	1610	59	48
1.5	886	60	310	0	2304	2348	85	73
2	966	102	414	0	3031	3084	115	95
Muskegon								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	277	34	108	0	882	897	30	25
1.5	303	50	163	0	1293	1312	46	37
2	323	67	217	0	1703	1727	62	49
Lansing								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	185	50	91	0	872	885	28	22
1.5	219	24	137	0	1285	1299	38	32
2	256	172	182	0	1686	1714	60	45
Kalamazoo								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	267	41	106	0	993	1009	31	25
1.5	299	12	159	0	1464	1480	42	39
2	314	180	212	0	1920	1952	69	55

Grand Rapids								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	405	22	306	0	2858	2883	82	71
1.5	483	7	458	0	4233	4265	121	105
2	550	99	611	0	5600	5646	168	143
Flint								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	294	56	175	0	1549	1569	50	41
1.5	342	40	262	0	2281	2304	71	60
2	380	54	350	0	3010	3038	96	81

TABLE 8 Cost breakdown for the case of 6 hour SLB and the solar panels in Michigan

Saginaw								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	717	439	207	0	1539	1602	94	56
1.5	861	674	310	0	2248	2336	141	85
2	951	879	414	0	2960	3068	186	111
Muskegon								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	273	235	108	0	863	892	49	30
1.5	303	353	163	0	1264	1305	75	44
2	323	471	217	0	1666	1718	99	58
Lansing								

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	185	198	91	0	858	881	42	26
1.5	219	297	137	0	1260	1293	63	38
2	256	396	182	0	1663	1706	83	53

Kalamazoo

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	263	230	106	0	976	1004	48	30
1.5	299	345	159	0	1433	1474	73	45
2	314	460	212	0	1891	1942	98	65

Grand Rapids

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	401	663	306	0	2800	2871	140	83
1.5	476	995	458	0	4144	4247	210	123
2	524	1327	611	0	5488	5621	280	168

Flint

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	286	380	175	0	1519	1562	80	48
1.5	338	570	262	0	2233	2294	119	70
2	368	760	350	0	2946	3024	160	95

BESS with 2 hour storage duration and solar panels

TABLE 9 Cost breakdown for the case of 2 hour NB and the solar panels in Michigan

Saginaw								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	427	82	207	0	1574	1601	59	57
1.5	503	182	310	0	2298	2339	91	82
2	845	145	414	0	3030	3083	116	96
Muskegon								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	277	5	108	0	884	897	28	25
1.5	303	8	163	0	1296	1312	43	37
2	323	11	217	0	1708	1727	57	49
Lansing								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	169	31	91	0	874	885	26	22
1.5	199	28	137	0	1285	1299	38	32
2	214	93	182	0	1693	1714	53	45
Kalamazoo								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	267	18	106	0	995	1009	29	25
1.5	299	4	159	0	1464	1480	42	39
2	323	63	212	0	1929	1952	60	55
Grand Rapids								

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	409	1	306	0	2860	2883	80	71
1.5	483	1	458	0	4233	4265	121	105
2	561	25	611	0	5605	5646	163	143
Flint								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	294	23	175	0	1552	1569	47	41
1.5	342	10	262	0	2283	2304	69	60
2	380	20	350	0	3013	3039	93	80

TABLE 10 Cost breakdown for the case of 2 hour SLB and the solar panels in Michigan

Saginaw								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	411	126	207	0	1570	1599	63	59
1.5	445	340	310	0	2285	2334	104	87
2	733	303	414	0	3017	3077	129	102
Muskegon								
EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	257	76	108	0	879	896	33	26
1.5	287	60	163	0	1292	1311	47	38
2	299	181	217	0	1696	1726	69	50
Lansing								

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	165	30	91	0	874	884	26	23
1.5	185	82	137	0	1281	1298	42	33
2	193	134	182	0	1689	1711	57	48

Kalamazoo

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	251	76	106	0	991	1008	33	26
1.5	283	74	159	0	1459	1479	47	40
2	308	97	212	0	1926	1951	63	56

Grand Rapids

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	395	52	306	0	2856	2883	84	71
1.5	455	111	458	0	4226	4264	128	106
2	506	220	611	0	5592	5645	176	144

Flint

EV Load Factor	Grid Cost ($k)	Battery Cost ($k)	Solar Panel Cost ($k)	Flywheel Cost ($k)	Electric Cost ($k/yr)	Total Cost ($k/yr)	Electricity Savings ($k/yr)	Total Savings ($k/yr)
1	286	36	175	0	1551	1569	48	41
1.5	308	162	262	0	2272	2303	80	61
2	356	105	350	0	3006	3037	100	82