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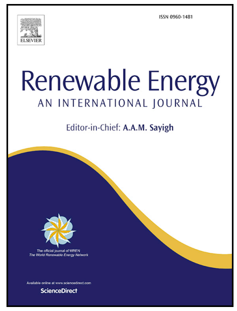

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Joshua M. Pearce: Conceptualization Ideas; Methodology; Resources;Writing - Original Draft Preparation; Writing - Review & Editing; Supervision; Funding acquisition

Swaraj Sanjay Deshmukh: Methodology; Software; Validation; Formal analysis; Investigation; Data Curation; Writing - Original Draft Preparation; Writing - Review & Editing; Visualization.

Electric Vehicle Charging Potential from Retail Parking Lot Solar Photovoltaic Awnings

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Abstract

This study investigates the energy related aspects of developing electric vehicle (EV) charging stations powered with solar photovoltaic (PV) canopies built on the parking infrastructure of large-scale retailers. A technical analysis is performed on parking lot areas located in the highest EV market coupled with charge station rates and capacities of the top ten EV. The results of a case study show a potential of 3.1 MW per Walmart Supercenter in the U.S., which could provide solar electricity for ~100 EV charging stations. In the entire U.S., Walmart could potentially deploy 11.1GW of solar canopies over only their Supercenter parking lots providing over 346,000 EV charging stations with solar electricity for their customers covering 90% of the American public living within 15 miles of a Walmart. This novel model could be adopted by any box store with the solar electricity sold for EV charging at a profit solving community charging challenges. In addition, however, the results for the first time indicate store owners could increase store selection and profit by providing free PV-EV charging for their customers with four mechanisms. Overall the results of this study are promising, but future work is needed to provide more granular quantification of the benefits of this approach.

Keywords: solar; photovoltaic; electric vehicle; electric vehicle charging; solar canopy; solar parking lot

1. Introduction

Solar photovoltaic (PV) technology is a now well-established sustainable energy source [1-4]. Although historically it has seen restricted deployment due to economics [5], rapid cost declines [6] have reduced the levelized cost of solar electricity [7] below those of conventional power sources [8,9]. Cost declines follow from a rapid learning curve in the PV industry [10,11] and technical improvements in conversion efficiency at the cell [12] and module levels [13]. By 2018 more than ten modules were on the market with over 20% conversion efficiency from various manufacturers [14]. Thus, PV has been a major recent driver [9,15] of higher penetration of renewable energy into the U.S. national energy market [16]. Although improved financing mechanisms [17-19] have enabled PV technology to be deployed to a greater fraction of the residential and small business market, the majority of PV is on the industrial/utility scale [20].

The growth of low-cost solar has been a welcome contribution to the U.S. electrical supply, as although the current COVID-19 pandemic is clouding the U.S. Energy Information Administration's predictions in the short term [21], over the long-term electricity use is expected to increase in part because as the number of electric vehicles (EVs) is expected to skyrocket [22] there would be a transition from oil to electricity increasing electric demand [23,24]. EVs and plug-in hybrid electric vehicles (PHEV) are becoming increasingly important as the sales of EVs are rapidly increasing their share (2.2%) of the global vehicle market [25]. By 2040 the electric vehicle count in the market will increase up to 30% [26]. As solar is the fastest growing electricity source set to displace fossil fuels, a challenge is presented to identify the surface area needed to produce thousands of TWhs of electricity [27]. These demands can in part be met with aggressive building integrated PV (BIPV) and rooftop PV [28-33], however, more surface area is needed [34]. One method to increase potential PV area, particularly well-suited for EVs is to utilize the stranded assets of non-productive parking lot areas as solar farms with PV canopies, enabling sustainable energy production while preserving their function to park automobiles [35-39]. There is already substantial research into the design and optimization of solar systems to charge EVs as a sustainable strategy [40] including at the workplace [41-43] because EVs could be integrated to the grid to solve intermittency challenges via vehicle-to-grid implementations [45-50]. In addition, technical studies have shown the viability of the approach [39,51,52].

To build on this previous work, this study provides a novel more-detailed investigation into the energy-related aspects of developing EV charging stations powered from solar PV canopies built on the parking infrastructure of large-scale retailers such as Walmart, Ikea, BestBuy, and Costco. These retailers have large warehouse-sized stores with larger parking areas, which have a substantial potential of raising PV canopies. Of these stores Walmart is used here as a case study because of its size. Walmart is larger than Home Depot, Kroger, Target, Sears, Costco, and K-Mart combined [53]. This is the first analysis to specifically look at the synergies of PV and EV charging stations as a general model for large-scale retail using parking lot PV canopies. A technical analysis is performed on parking lot areas located in the highest EV market coupled with charge station rates and the charge capacities of the top ten EV to determine: i) the solar energy generation potential of the most dense PV parking lot canopy (or awning) designs using standard and high-efficiency silicon-based PV; ii) the number of EV charging stations that could be supported by PV-covered parking lots using these canopies as well as the percentage of parking customers that could be served, and iii) the percent of charging capable during a range of shopping times as well as the distance the EVs could travel on that charge to determine the benefits to the customer. These results of this novel model are presented and discussed in the context of the potential benefits of retailers adopting this approach including reducing the heat island effect while increasing the comfort of their customers be shielding them from precipitation, increasing store selection due to green consumerism and EV ownership, and increasing time shopping of the latter.

2. Methods and Calculations

The city of San Jose, California has been selected for study because according to the survey by the International Council of Clean Transportation, it is one of the cities with the highest number of EV as well as electric charging stations [54]. San Jose already has over 20% EV penetration in the market [22]. Electricity produced by PV canopies using the available solar flux [55] will be compared to the energy consumed by EV charging stations to estimate the number of EV that can be charged based on the average time a car is parked in a retail store parking lot. In the following subsections all of the assumptions and references for input data are defined for the case study.

2.1 Locations

Wal-Mart has approximately 5,355 stores in the U.S. of which 3,571 are Super Centers, 687 are neighborhood markets and 376 are discount stores [56]. The study is based on the parking lots of three different Walmart stores in San Jose based on the most common types of stores (two Super Centers and one Neighborhood Market). The detailed locations of the stores are summarized in Table 1.

Table 1: Location details for three case study stores

Location	**Walmart 1 (Supercenter)**	**Walmart 2 (Supercenter)**	**Walmart 3 (Neighborhood Market)**
Requested location	777 Story Rd, San Jose, CA 95122	5095 Almaden Expy, San Jose, CA, 95118	4080 Stevens Creek Blvd, San Jose, CA 95129
Weather data source	Lat, Lon: 37.33, -121.86 0.1 mi	Lat, Lon: 37.25, -121.86 0.1 mi	Lat, Lon: 37.33, -121.98 0.1 mi
Latitude	37.33˚N	37.25˚N	37.33˚N
Longitude	121.86˚W	121.86˚W	121.98˚W

2.2 Software for Area and Energy Analysis

PV Watts (Version 6.1.3) [57] software has been used in this study to determine the number of vehicles that can be parked in the parking lots of the case study stores, the area of the parking lots and an estimate of the solar electricity output from the installation of PV canopies. A previous study of PV canopies in parking lot areas for Walmart facilities in the U.S found the average parking lot area to be 20,777 +/- 5047 m^2 [36]. The average parking lot size for one vehicle is considered around 12 – 15 m^2 [58]. The data given can be used to estimate an approximate power of PV modules that can be installed on the parking facility, the solar electricity and also the number of cars that can be charged in the parking facility based on the charging rates and charging capacity of the EV's. It is assumed these are grid tied systems.

The PV system specifications for each store was kept as consistent as possible as detailed in Table 2.

Table 2: PV specifications for three case study stores

PV System Specifications	Walmart 1 (Super Center)	Walmart 2 (Super Center)	Walmart 3 (Neighborhood market)
DC System Size [1]	4,712.6 kW	1,532.2 kW	1,137.6 kW
Module Type	Case 1: Standard 15% nominal efficiency Case 2: Premium 19% nominal efficiency		
Fixed Array Tilt	Fixed (Open Rack) 7˚ [59]		
Array Azimuth	180˚		
System Losses	14.08 % (System losses consider various categories such as soiling, snow, wiring, shading, mismatch, connections, light-induced degradation, nameplate rating, age, availability [57])		
Inverter Efficiency	96 % inverter efficiency is the default value for the selected location [57]		
DC to AC Size Ratio	1.2 [57]		

[1] As determined from PVWatts after area was specified

2.3 Structure

There are five main categories of solar PV parking canopy-based structures [60]: i) tee, ii) truss, iii) long span, iv) inverted, and v) garage. The long span structure as shown in Figure 1 is used in this study as it covers the maximum area of the parking lot as it covers not only parking spots but also the driving aisles [59,61].

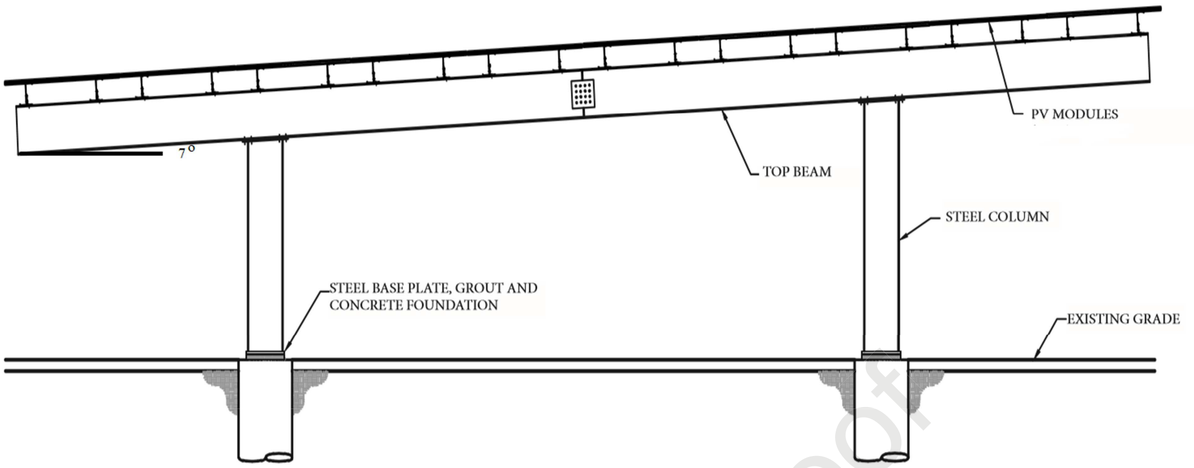

Figure 1. Cross section schematic of long span structure (adapted with permission from RBI Solar Inc.). PV can be closed packed over entire parking area including driveways between parking spots.

2.4 EV Charging Stations

There are three major categories of chargers generally accepted in the EV industry, based on the maximum amount of power the charger provides to the battery from the grid. Level 1 provides charging through a 120 V AC plug and can deliver 2 to 5 miles of range per hour of charging so a full charge requires between 8 and 20 hours with a charging rate is approximately 1kW [62]. Level 2 provides charging through a 240 V (for residential) or 208 V (for commercial) plug and requires installation of additional charging equipment. Level 2 delivers 10 to 20 miles of range per hour of charging and a full charge can be reached in 3 and 8 hours and the charging rates are around 3kW to 20 kW [63]. Finally, DC fast chargers (level 3) provide charging as high up to 600 V, but most plug-in hybrid electric vehicles typically do not have fast charging capabilities, so they were not considered. In addition, as level 1 charging times are slower and have prolonged charge times, the ratio of the effort to the reward for plugging in the EV is reduced for the consumer. The faster the charging the greater the reward for a given inconvenience of plugging in.

After existing theory about the EV's, PHEV's and their energy consumption is surveyed by the IEA [62], it is determined that charging stations at the parking areas of commercial establishments need to have more rapid charging. This is to ensure that a significant charge percentage is made available to customers during an average shopping trip duration to ensure the effort / reward ratio is high enough to ensure customers will use the EV charging. Thus, here two different versions of level 2 charging stations are considered to capture the range in this level:

1) Clipper Creek – HCS 50 (240 V, 40 Amps, 9.6 kW) [64] and

2) Clipper Creek – HCS 80 (240 V, 64 Amps, 15.4 kW) [65].

The HCS 50 and 80 are model names. These EV charging stations are used to analyze charging times of ten of the most common commercial electric vehicles. Table 3 provides the range, battery capacity, and battery acceptance rate for the different electric vehicles analyzed here.

Table 3: Range per full charge, battery capacity and battery acceptance rates of some EV models [66-68].

EV	Range on full battery capacity (miles)	Battery Capacity (in kWh)	Battery Acceptance Rate (kW)
1. Tesla model S 100 Dual	335	100	17.2
2. Tesla model 3 (long range)	310	75	11.5
3. Tesla model X 100D	259	100	17.2
4. Chevrolet Bolt	238	60	7.2
5. Nissan leaf	151	40	6.6
6. Hyundai Kona	258	64	7.2
7. Ford Focus electric	115	33.5	6.6
8. Hyundai Ionic	124	28	6.6
9. Volkswagen e-Golf	125	35.8	7.2
10. Kia Soul 2020	243	64	7.2

Only the Tesla EVs could have charging rates greater than the HCS50. Thus, as the majority of EVs are not Teslas the HCS50 charging station was used to model the number of recommended stations using only solar for charging. In this way the majority of EV charging rates would be limited by the EV not the charging station. The number of charging stations, S, which can be installed at a retail store is given by:

$$S = \frac{E_d}{r \times h_d} \quad (1)$$

Where E_d is the PV-generated electricity per day measured in kWh by the PV canopy, r is the electricity transferred per hour by the charged station [kWh] and h_d is the estimated number of hours a given parking lot space is used per day. Here h_d is estimated to be 12. This calculation is repeated for all of the locations for every month. Using equation one ensures that the PV-generated electricity can be used by the EV charging station during normal shopping patterns.

In addition, to direct calculations for the EVs shown in Table 1, three EV battery capacities are evaluated to generalize the findings of 100 kWh, 60 kWh, and 40 kWh. S provides the capacity of EV charging stations the canopy can support and the number of customers that could be served.

2.5 Sensitivity analysis based on shopping time

One Walmart Supercenter receives around 10,000 visits by automobile per day, however this figure could vary from store to store [69] but on average a 1,858m^2. Walmart discount store results in 76,232 cars trips per week [70].

The number of miles that an EV owner could be expected to travel based on a charge while shopping is determined by:

$$M = \frac{r_{max} * R}{C} \tag{2}$$

Where r_{max} is the maximum charge rate [kWh/hr], which can be set by the limitations of either the EV or the charging station, R is the EV range in miles and C battery capacity in kWh.

On an average, a consumer spends one-hour shopping for groceries per week [71] and a sensitivity is run for 0.5 hour, 1.0 hour and 1.5 hour as the realistic range of shopping times.

The percentage of EV battery charged, P, is given by:

$$P = \left(\frac{r_{max} \times t}{C}\right) \times 100\% \tag{3}$$

Where t is the time spent charging in hours.

M and P provide insights into the potential benefit to customers that own an EV have for using a particular store and the cost benefit analysis of plugging into the charging station. The higher the number of miles a customer can travel on a given shopping trip charge the more attractive the potential to plug in the EV at the charging station at the store.

3. Results and Discussion

3.1 Potential PV canopy areas for case study retail stores

Using the methods outlined in the previous section conservative estimates of PV canopy areas were determined. This is shown in Figures 2-4 for the case study stores, where south is towards the bottom of all of the satellite images. The red areas in Figures 2-4 show the areas selected. In addition, in Figures 2-4 both the areas (m^2) in each parking lot that could conservatively be used for PV awnings and the PV system output capacity (kWdc) of each section of the parking lots of the case study retails stores, Walmart 1, 2, and 3, respectively.

Figure 2. System capacity for Walmart 1, Walmart Supercenter, 31,417 m^2 total area, 4,712.6 kW dc potential PV.

Figure 3. System capacity for Walmart 2 – Walmart Supercenter, 10,215 m^2 total area and 1,532.3 kW dc potential PV.

Figure 4. System capacity for Walmart 3 – Walmart Neighborhood market, 7,584 m^2 total area and 1,137.6 kW dc potential PV.

It should be pointed out that a relatively conservative approach was taken to identify where PV-parking lot canopies could be located. Areas were selected that were contiguous and areas over exterior driveways and near the store were excluded for potential shading complications. Future work could do more detailed simulations taking external structure shading into account, particularly if additional PV power is required for a particular location. Thus, more PV canopy area is available because canopies could extend closer to the stores at all three locations and be used to cover up more of the driveway portions of the lots. This conservative approach was taken for two reasons 1) to allow for relatively standard racking design and 2) in part to address a non-conservative assumption made in Table 1 concerning azimuth. As can be seen only Walmart 3 in Figure 4 has a lot that is amenable to a perfectly south facing PV array. In Figure 2 and 3 the arrays would need to be oriented slightly off south or the system would need to be non-square to the lots. The annual production is not overly sensitive to a few degrees difference in azimuth angle and there would be additional parking lot surface area that could be used to achieve the areas shown in Figure 2 and 3.

3.2 Potential PV-generated electricity for case study PV canopies

The PV electricity produced each month is simulated using the input parameters from Tables 1 and 2 and plotted in Figure 4 for the areas available for a PV awning shown Figure 2-4. It is interesting to note that the solar production is directly dependent on the available parking lot area, which is not overly dependent on the type of Walmart store. As seen in Figure 5 and 6 the PV output for Walmart 2 and 3 are similar despite one being a super center and the other a neighborhood market. Supercenters and their parking lots can get quite large as seen in Figure 2 and the resultant output shown in the blue line on Figure 5. The average super center parking area is roughly the average of Walmart 1 and 2.

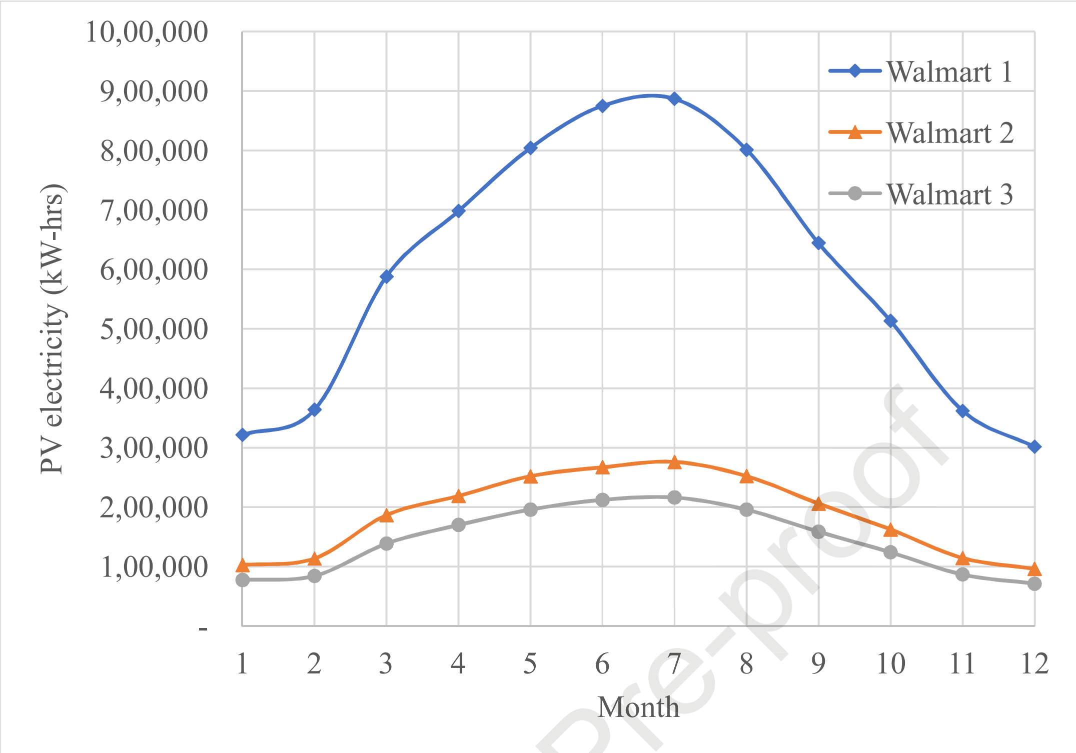

Figure 5. PV electricity (kW-hrs) produced from parking lot awning solar arrays in case study retail stores.

3.3 EV charging stations supported by PV awnings

The number of charging stations that the PV awnings can supply 100% of the electricity for charging 12 hours per day varies by time of year and time of shopping. This is plotted for the average time shopping (1 hour) as well as for 30 min and 90 min in Figure 5 for all three case study stores as a function of month.

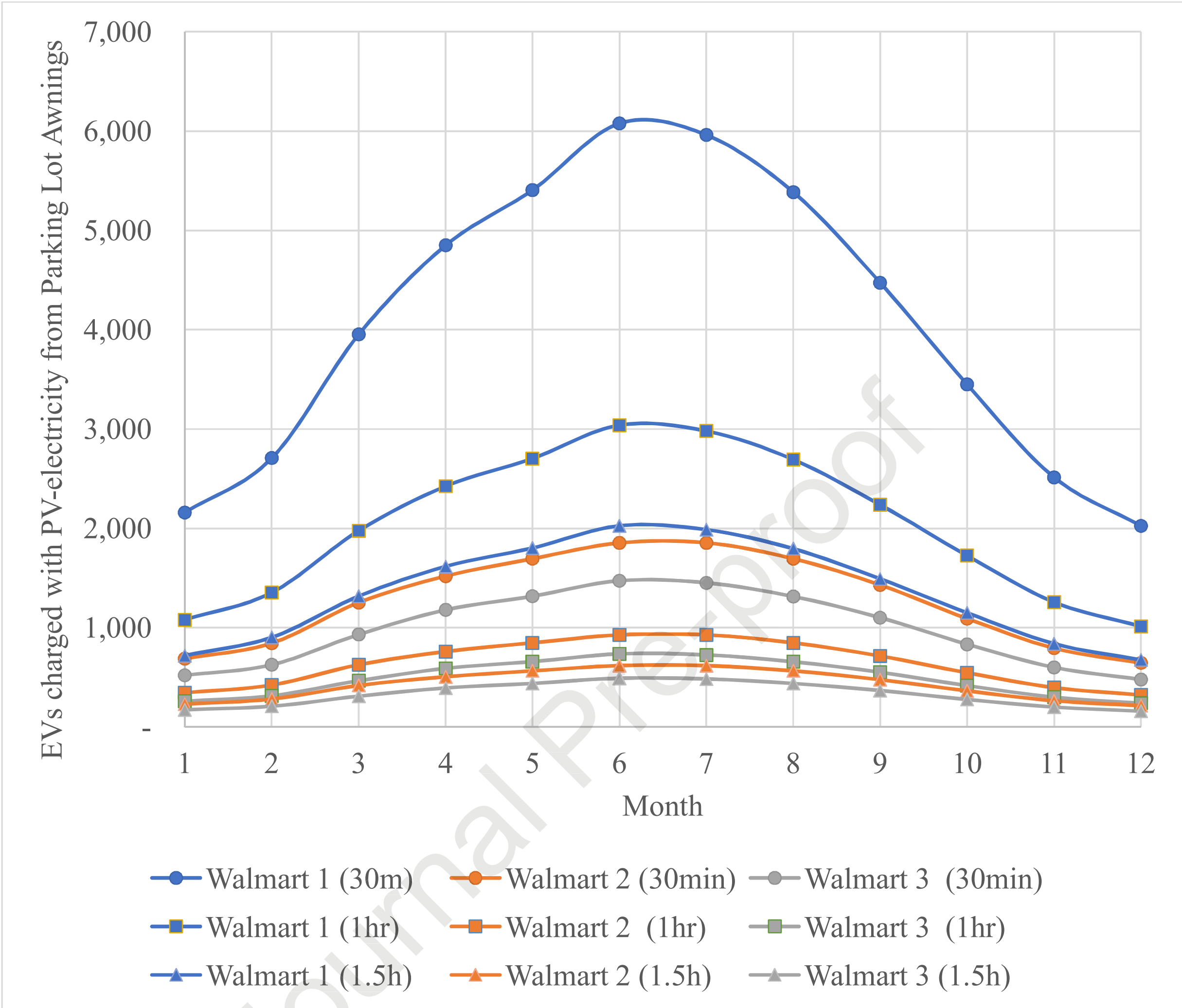

Figure 6. EVs charged with PV electricity from parking lot canopies for three case study retail stores.

As can be seen in Figure 6 the number of cars that are able to be charged is highly dependent on both the PV canopy surface area and the charging time. The average number of cars that Walmart 1, 2 and 3, could service with solar electricity per day was 2040, 640 and 493 for 1-hour shopping trips, respectively. For 30-minute shopping trips these values increase to 4,080, 1,280 and 985, respectively.

3.4 Benefits and incentives of charging of representative EVs

Table 4 shows the charging capacity and charging time for the ten electric vehicles based on the output of the chargers.

Table 4. Charging times for Electric vehicles

Name of the EV	**Battery Capacity** (in kWh)	**Battery Acceptance rate** (kW)	**Time to Full charge (hr) at 240V**		**Amount of charge gained per hour of charging (kWh/hour)**	
			HCS 50 9.6 kW delivery rate	**HCS 80 15.4 kW delivery rate**	**HCS 50 module**	**HCS 80 module**
Tesla model S 100 Dual	100	17.2	10.4	6.5	9.61	15.38
Tesla model 3 (long range)	75	11.5	7.8	4.87	9.61	15.4
Tesla model X 100D	100	17.2	10.4	6.5	9.61	15.38
Chevrolet Bolt	60	7.2	8.3	8.3	7.2	7.2
Nissan leaf	40	6.6	6	6	6.6	6.6
Hyundai Kona	64	7.2	8.8	8.8	7.2	7.2
Ford Focus electric	33.5	6.6	5	5	6.7	6.7
Hyundai Ionic	28	6.6	4.2	4.2	6.6	6.6
Volkswagen e-Golf	35.8	7.2	4.9	4.9	7.2	7.2
Kia Soul 2020	64	7.2	8.8	8.8	7.2	7.2

As can be seen in Table 4, fully charging from empty any of the top ten EVs while making a normal shopping trip is not possible. The fastest charging time was 4.2 hours for the Hyundai Ionic. The longest was 10.4 hours for two of the Tesla models. It can also be seen that only the Tesla models could take advantage of the 15.4 kW delivery rate of the HCS 80 charging station. This result can be viewed two ways. First, all of the cars could be adequately serviced by the HCS 50, which would reduce costs for the installation. However, as a faster charging rate is a benefit, it can be presumed that as EVs mature more will move to the higher rates already utilized by the Tesla vehicles. Thus, for long-term investments higher charging rate chargers may already be justified. Future work is needed to quantify this.

Table 5 shows the amount of charge gained and the number of miles that each of the analyzed EV would be able to travel after charging for the average shopping time (1 hour) as a function of the charging station. As can be seen all of the cars were able to travel at least 20 miles on the charge they could gain from a 1-hour shopping trip. This is important as roughly 90% of all Americans live within 15 miles of a Walmart [53]. This means that for many shoppers with an EV, the trip to Walmart and back would potentially have zero automobile-related energy costs.

The lowest distance found was for the Ford Focus electric at just 23 miles as seen in Table 5. The Tesla vehicles, however, showed the advantages of the HCS 80 rapid charging. Whereas the Tesla miles for 1-hour charge were near many of the other vehicles on the HCS 50 ranging from about 25-40 miles, on the HCS 80 they could travel about 40-63 miles. This also highlights the advantage that Tesla vehicles have now and points to a likely improvement in performance for future models of EVs as well as making the viability of this more approach greater with time.

Table 5. Table for number of miles per hour of charge

Name of the EV	**Range for full charge** (miles)	**Battery Capacity** (in kWh)	**Amount of charge gained per hour of charging**		**Number of miles per hour of charge** (miles)	
			HCS 50	**HCS 80**	**HCS 50**	**HCS 80**
Tesla model S 100 Dual	335	100	9.61	15.38	32.19	51.52
Tesla model 3 (long range)	310	75	9.61	15.4	39.72	63.65
Tesla model X 100D	259	100	9.61	15.38	24.88	39.83
Chevrolet Bolt	238	60	7.2	7.2	28.56	28.56
Nissan leaf	151	40	6.6	6.6	24.91	24.91
Hyundai Kona	258	64	7.2	7.2	29.02	29.02
Ford Focus electric	115	33.5	6.7	6.7	23	23
Hyundai Ionic	124	28	6.6	6.6	29.22	29.22
Volkswagen e-Golf	125	35.8	7.2	7.2	25.13	25.13

Kia Soul 2020	243	64	7.2	7.2	27.33	27.33

It is clear, however, from Table 5 that having free EV charging while shopping at retail stores purchase other products would be a substantial incentive to a) shop at the store and b) take the effort to plug in the vehicle while there. Another way to observe this incentive is by the percent charge as a function of shopping time shown in Table 6. If getting 'free' electricity for their EVs is valuable enough to customers they may choose to spend a longer time shopping. There is already an evidence that the longer time consumers spend in a store, the more money consumers spend [72]. Future work is needed to quantify this benefit for retail store owners.

Table 6. Number of hours spent shopping and percentage of EV battery charged.

Average number of hours shopping (min)	**Percentage of EV battery charged** (%)					
	100 kWh EV		**60 kWh EV**		**40 kWh EV**	
	HCS 50	**HCS 80**	**HCS 50**	**HCS 80**	**HCS 50**	**HCS 80**
30	4.8	7.69	6	6	8.25	8.25
60	9.6	15.38	12	12	16.5	16.5
90	14.4	23	18	18	24.75	24.75

3.5 Solar-powered EV charging spot availability

As can be seen by the results in Figure 4, the peak production is in July and the minimum is in December for all locations. These values are used to get a minimum and maximum number of EV charging spots that the PV arrays could cover for electricity consumption for each case study store. These values, which could provide starting points for designs based on microgrids along with average, which is more appropriate for grid-tied (particularly net metered systems) is shown in Table 7. In addition, the percent of total parking spots is shown in Table 7 for each of the scenarios.

Table 7. The solar-powered EV charging spots available at each case study location based off the lowest, highest and average solar flux month.

	Walmart 1		**Walmart 2**		**Walmart 3**	
	Spots	**Percent**	**Spots**	**Percent**	**Spots**	**Percent**
Total Parking Spots	944		359		237	
December (lowest)	196	21%	62	17%	20	8%
Average	170	18%	53	15%	41	17%
June (highest)	253	27%	77	22%	61	26%

Figures 7-9 depict the parking spots, which could be serviced with a charging station powered by a PV canopy in Walmarts 1, 2 and 3, respectively.

As can be seen in Table 7 the percent of parking spots that can conservatively be serviced with a solar-powered PV parking lot canopy is between 8% and 21% for the case studies analyzed in the winter and between 22% and 27% in the summer. On average between 15% and 18% of parking spots could be serviced with a solar powered awning. This is a substantial fraction of the parking lots as shown in Figures 7-9. The areas of PV-powered EV charging stations is color coded in Figures 7-9 where red is for December (lowest), yellow is for the average, and green is for June (highest).

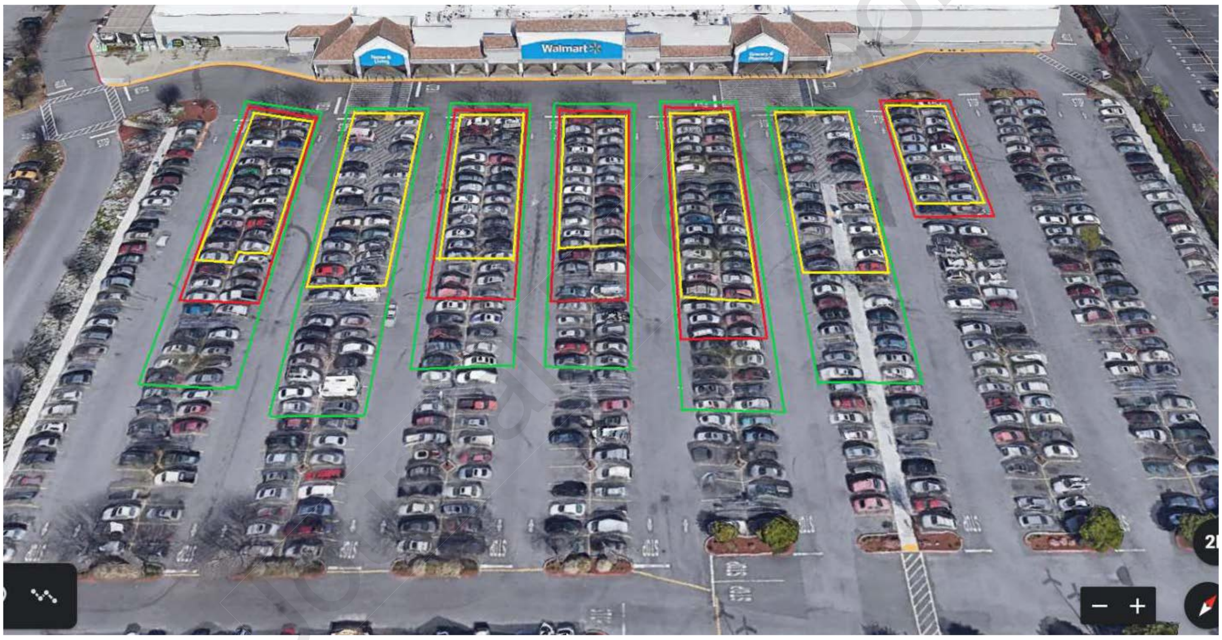

Figure 7. Parking spots for Walmart 1 that can serviced with an EV charging powered with a PV canopy over the entire parking lot where red: December (lowest), yellow: average, and green: June (highest).

As can be seen in Figure 7, most of the main lot for Walmart 1 (it does have several as shown in Figure 2) can be covered with charging stations in the summer and a reasonable number in the winter as well. It is also interesting to note the high usage for the parking lot, where only a few spaces in this main lot are empty.

If such a store covers its parking lots with PV canopies as well as install EV chargers in the most used parking spots it is reasonable to assume it will be viewed as an environmentally friendly store and benefit from the resultant inherent green marketing [74-76], which would in turn be expected to offer it a competitive advantage [77]. Indeed, the entire PV-EV system can be thought of as the equivalent a store-size ecolabel [78]. This is because the green consumerism effect [79-81] is so strong that it the self-identity of customers [82] can be strengthened by the act of shopping at a green store [83] or in this case, parking to shop at such a store under a solar canopy. This effect would likely be strengthened further for customers solar-charging their EVs. Quantifying this competitive advantage is an urgent area of future work as well as the potential second-order improved environmental behavior [84,85](e.g. would customers of such a store be more likely to purchase an EV, install PV on their own home or business, or partake of other more sustainable behaviors more frequently?). In addition, to green consumers, the solar-powered EV charging stations would provide a direct incentive for all EV and PHEV owners to shop at the store even if they only chose EV based on non-environmental considerations [86]. This is already a significant potential market in San Jose, which has 21% electric vehicles and this is increasing rapidly elsewhere [54].

Figure 8. Parking spots for Walmart 2 that can serviced with an EV charging powered with a PV canopy over the entire parking lot where red: December (lowest), yellow: average, and green: June (highest).

As can be seen in Figure 8 where the Walmart Super Center only has one lot, only the premium (most used) parking spots would be able to handle powered EV stations from the PV rooftop awning. It is also interesting to note that this is the only parking lot of the three case studies that has planted trees, which provide shading for cars. There appears to be preferential parking near trees to reduce the temperature of the parked automobiles by customers. This is indicative of one of the other benefits of having a PV canopy over the whole lot all the cars would be shaded and all the spots would be cooler and thus reduce air conditioning load of the vehicles as compared to parking in full sunlight. This is supported by the literature that points out that PV canopies can be expected to reduce the urban heat island effect caused by dark paved surfaces [87]. In fact, a recent study by Golden et al. [88] indicated that PV provides a greater thermal reduction benefit during the diurnal cycle in comparison to urban forestry. The benefits of a shielded parking lot are not restricted to sunny California. In all regions shielded parking would protect customers from precipitation whether rain in mild climates or snow, sleet and hail in winter environments. It would thus be expected that customers given two equivalent stores to choose from would favor the store with the more comfortable PV-shielded parking lot. Quantifying both this energy conservation opportunity (reduced energy use for AC within cars in the summer and reduced idling vehicles while customers scrape snow and ice off their windshields in some winter locations) as well as the increased use of the retail store compared to stores without shielding for customer vehicles is left for future work. With trees being taken out of the parking decision equation it is likely that customers would park closest to the entrance to the store as is indicated by the parking observed in Figure 9.

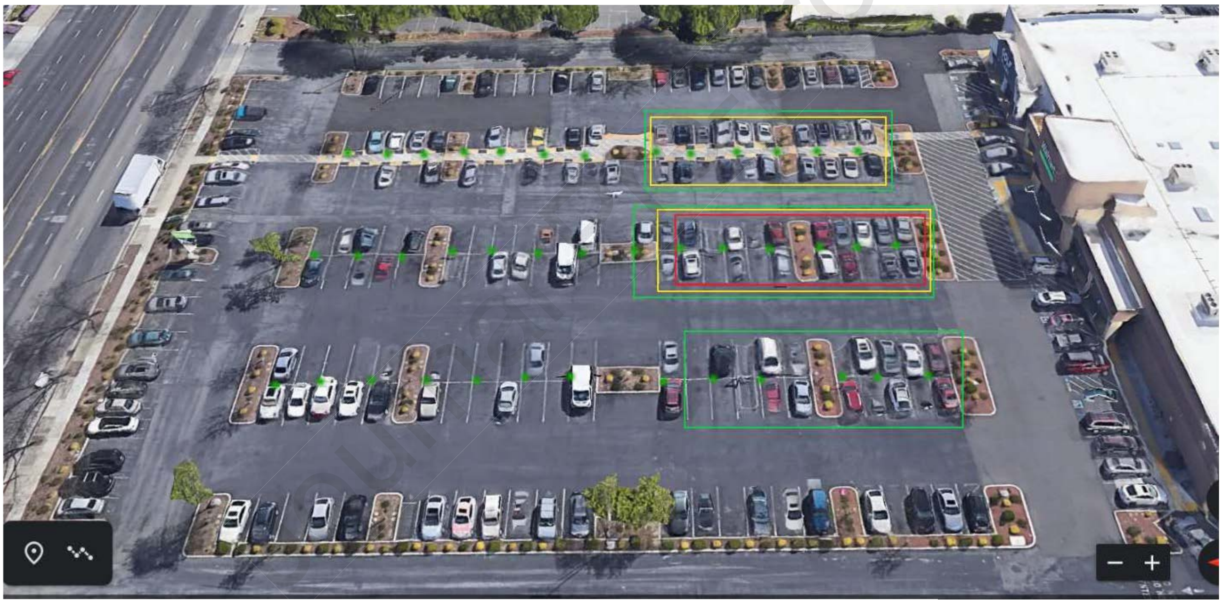

Figure 9. Parking spots for Walmart 3 that can serviced with an EV charging powered with a PV canopy over the entire parking lot where boxes of red: December (lowest), yellow: average, and green: June (highest). The green dots represent potential locations for chargers covering 4 spots in the average scenario.

Figure 9 shows the neighborhood small-size Walmart with a relatively small parking lot. Again, only a small fraction of the lot could have EV charging stations powered by the PV canopy. To make PV-EV charging accessible to more of their customers one approach could be to place the charging stations such that there is one for every four cars as indicated by the green circles in Figure 8. Likewise, half this area could be enabled with EV chargers covering two spots. Arranging charging stations this way would ensure that EV owners were not blocked from using chargers by non-EVs parked in charging spots. It would also entail no behavioral change in consumers or additional signage (e.g. “Parking reserved for EV”) that could have unintended negative consequences. In the short term these spots sharing chargers would provide a greater percentage of the entire lot accessible for charging, but would require more capital costs for the wire runs than simply locating them closest to the entrance of the store. In the long term as all vehicles are transitioned first to PHEVs and then EVs retail stores would ideally have a charger for each vehicle so the charging station locations could be designed to add more charging stations with time. Having the charging stations dispersed initially, would thus save capital costs in the future because wire runs would already be laid beneath the parking lot.

3.6 Scale up of EV charging for retail parking with PVawnings

The results of using higher-efficiency PV modules are shown in Table 8. As discussed above, PV efficiencies are increasing at the lab and module levels and new adaptations of existing technologies like black silicon are expected to further reduce costs while increasing efficiencies further [89]. As can be seen in Table 8 using commercially available higher efficiency cells the PV output can be increased by 2-3% from those calculated with low efficiency PV.

Table 8. Result for Walmart case studies comparing standard and higher-efficiency PV modules.

Parameters observed	**Walmart 1**	**Walmart 2**	**Walmart 3**
Standard efficiency PV annual output (kWh/year)	7,159,982	2,246,617	1,729,370
High efficiency PV annual output (kWh/year)	7,311,601	2,315,156	1,764,325
Percent increased output	2.11 %	3.05 %	2.02 %

The average area available in a Walmart Supercenters for solar canopies for case study 1 and 2 is 20,816 m^2 which is within error of Krishnan et al. [36] earlier estimate 20,777 +/- 5047 m^2. Thus, the average results of case study 1 and 2 can be used for rough estimates on the potential for EV charging across Walmart’s fleet of super centers. This would result in about 3.1 MW of PV per super center store as the solar potential for the parking lots. Care must be taken when converting this to energy and thus charging potential as the case study location, San Jose, has a strong solar flux of about 5.12 kWh/m^2/day and the national population averaged solar flux is 4.499 kWh/m^2/day [90]. Thus, on average a Walmart Superstore would be expected to service about 87% of the average of case study 1 and 2 or 98 EV charging stations per store. Walmart has approximately 3,571 Super Centers in the U.S., indicating that Walmart could potentially deploy 11.1GW of solar canopies over their Supercenter parking lots and provide aver 346,000 EV charging stations with solar electricity for their customers. This potential is intriguing for both Walmart alone as this would provide charging stations within 15 miles of 90% of the American population. If other box store retailers adopted this approach it would potentially solve many of the challenges with EV charging station placement [91].

Electricity generated from solar covered parking lots could be sold at a profit based on previous work [36] coupled with current PV costs well under $0.20/W [92] and estimated solar canopy racking costs of about $1.10/W [93]. Thus, PV canopies coupled to EV charging stations could provide additional store-related revenue as indicated by the levelized cost of electricity from PV from other studies of PV canopies alone [36]. The revenues would be substantial if in one of the limited jurisdictions with full net metering in the U.S. [94]. The results, however, also indicate store owners could profit from providing free solar electricity charging stations for their customers based on four mechanisms: i) increasing the comfort of their customers by providing shading in summer and precipitation avoidance, which may increase store selection, ii) provide a clear mode of green consumerism which may also increase store selection, iii) provide an incentive for the rapidly growing class of PHEV and EV owners to preferentially shop at the store, and iv) increase the time shopping and thus money spent by PHEV/EV owners at the store to enable more charging. Future work is needed to quantify all four of these effects. Although this study focused on Walmart case studies, the same benefits would accrue to any box-style retailer. For retailers that are interested in determining the economic performance for a PV canopy at a specific location, the methodology shown here can be used to determine their store's technical potential. Then the retailer would acquire quotes for installers to populate the economic analysis in PVWatts with real values, being sure to include any federal, state or local incentives in the costs. The potential profitability of PV-generated electricity by any box store adopting solar canopy coupled EV charging stations would be determined by the costs of the racks, charging stations and the PV spot prices. The results, however, indicate store owners could profit from providing free solar electricity charging stations for their customers with four mechanisms detailed above. Quantifying the economic value of these mechanisms at a geographically granular scale is a rich area of future work. There is however, substantial evidence using consumer gasoline vehicle behavior that indicates the free PV-powered EV charging would increase store selection and shopping time. In a survey by the Association for Convenience & Fuel Retailing [95] 63% of drivers would drive 5 minutes out of their way, each way, to save only 5 cents per gallon and 36% would drive 10 minutes out of the way to save the same amount. This is very little savings and possibly none at all when time and extra gas for the drive (10-minute and 20-minute round trip, respectively) are considered. It seems reasonable to assume that an EV driver would be willing to make similar time investments for free charges, particularly if that investment is time substituted shopping at another retail store. These effects need to be quantified in future work (e.g. increased revenue from increased shopping time needed to charge an EV).

3.7 Limitations

Although the results of this study appear to be extremely promising it did have several limitations. First, the selection of case studies was based on the largest EV market as it was the most relevant and store owners in this region would be best suited for immediate deployment. However, this region is also a high solar flux location and future work needs to evaluate locations with a range of solar insolations. Past work has indicated that based on current PV system costs, parking lot PV canopies are economically viable in their own [36]. This work evaluated the technical potential of using such PV canopies over the parking lots of retail stores to provide electricity for EV charging stations, but future work is needed to analyze the economics of deploying such systems. For example, is it in the store owners' best interest to provide charging stations for free or to charge a fee? Might it benefit particular automobile manufacturers like Tesla [96] to subsidize the deployment of higher rate charging stations? To answer such questions there are parameters that remain as variables and unknown and would need to be determined for specific cases. These parameters include number of customers visiting the facility, number of miles per hour of charge, number of electric vehicles in the location, average time spent by the customer in a specific store, and charge present already in the EV. Then as pointed out in the vehicle to grid studies referenced earlier there is considerable future work to look at the potential impact of such systems on the grid itself. Finally, there are unanswered questions on the impact of the solar powered EV charging on consumer behavior. Will consumers preferentially select to shop at such a store? Will consumers increase shopping time and by how much? Will this increased shopping time result in increased sales and by how much as a function of type of store? Will the development of PV-EV coupled systems with high visibility accelerate both PV and EV adoption by helping educate and normalize environmentally responsible behavior?

4. Conclusions

The results of this study have shown that between 15 and 18% of the average Walmart parking lot could be serviced with solar energy powered EV charging stations in one of the largest EV markets in the U.S. This is possible with the lowest cost and low performance PV modules now and is only expected to increase in the future. The case study results for San Jose California were extremely promising as it is the largest EV market in the U.S. These results, however, can be applied to the rest of the U.S. and show a potential of 3.1 MW per Walmart Supercenter that could provide solar electricity for about 100 EV charging stations. Nationally the results of this study show Walmart could potentially deploy 11.1 GW of solar canopies over only their Supercenter parking lots and provide over 346,000 EV charging stations with solar electricity for their customers. This would provide community charging for 90% of the American public that live with 15 miles of a Walmart. The same approach would apply to the other Walmart types of stores as well as any other box-style retailers, which could potentially provide all the charging necessary to make EVs more common. Overall the results of this study are extremely promising but future work is needed to provide more granular quantification of the benefits of this approach and experimental validation.

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Highlights

Investigates electric vehicle (EV) charging stations + solar photovoltaic (PV) parking lot canopies
Potential 3.1 MW PV and 100 EV charging stations per US Walmart Supercenter
Entire U.S., Walmart could deploy 11.1GW of solar canopies
Supercenter parking lot PV provide electricity for over 346,000 EV charging stations
Cover 90% of the American public with solar-EV charging living within 15 miles of a Walmart.

Declaration of interests

X☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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