Technical, Financial, and Environmental Feasibility Analysis of Photovoltaic EV Charging Stations With Energy Storage in China and the United States

Alonzo Sierra, Cihan Gercek, Karst Geurs, and Angèle Reinders

***Abstract*—This study assesses the feasibility of photovoltaic (PV) charging stations with local battery storage for electric vehicles (EVs) located in the United States and China using a simulation model that estimates the system's energy balance, yearly energy costs, and cumulative CO_2 emissions in different scenarios based on the system's PV energy share, assuming silicon PV modules, and 5 kWh of storage capacity. Results show that systems located in commercial or office parking lots and used for charging EVs during working hours can be a feasible solution in all locations from a technical, financial, and environmental perspective in comparison with not only gasoline-fueled vehicles but also with grid-only charging. PV shares of 50% and 75% are achievable in all locations with PV array sizes in the order of 1–1.5 kW_p, whereas a 100% PV share is possible but might result in high system costs. Scenarios with PV charging and local storage show emissions reductions of 60%–93% in the USA and 28%–93% in China compared with a gasoline-fueled vehicle.**

***Index Terms*—Battery energy storage, CO_2 emissions, electric mobility, photovoltaic (PV) systems, simulation.**

I. Introduction

The transport sector is currently responsible for almost a quarter of global energy-related CO_2 emissions [1], and there are high hopes on reducing these emissions through the use of electric vehicles (EVs) that represent a low-CO_2 alternative to internal combustion engine vehicles (ICEVs). Depending on the location, EV use could potentially further reduce CO_2 emissions by charging with a renewable energy source such as solar photovoltaic (PV) systems. This could also have added benefits such as reducing local grid overloading, providing self-sufficiency and increasing energy self-consumption [2], [3]. Adding battery energy storage systems (BESS) to these charging stations will increase the share of solar energy supplied to EVs while increasing the grid's resilience to the intrinsic intermittency of PV power [4], [5].

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TABLE I
Locations Selected for the Present Study [10]

Location	Coordinates	GHI [kWh/m^2]	Optimal Tilt [°]	In-plane irradiation* [kWh/m^2]
San Francisco	37.78, -122.42	1810	35°	2110
Chicago	41.88, -87.62	1440	35°	1640
Guangzhou	23.13, 113.26	1430	21°	1490
Xi'an	34.35, 108.94	1410	33°	1580

*At optimal tilt angle.

While there exist several studies in the literature analyzing the performance of PV-powered vehicle charging stations [3], [6], [7], few of them have assessed the financial and environmental impact that these systems could have in practice. This is particularly important considering the influence a given location has on aspects such as irradiation, electricity prices, and CO_2 emissions per kWh generated by the local energy mix, which can be decisive in determining the feasibility of installing a PV charging station.

To this end, we developed a model to analyze these aspects in an interdisciplinary manner; this model has been published in the *Progress in Photovoltaics* journal [8]. In our previous work, we analyzed the feasibility of PV charged EVs in two locations in Europe (Norway and the Netherlands) as well as in Brazil and Australia. The present study will add to these results by exploring the potential of stationary PV charging of EVs in two locations in the United States (San Francisco and Chicago) and two in China (Guangzhou and Xi'an). With 1.1 and 2.3 million units, respectively, these two countries had the largest EV fleets in the world in 2018, which represented over 60% of the global EV stock [9], making them interesting locations for the deployment of PV charging stations. Because of their geographic dimensions and the expected variability in conditions such as irradiation and system costs, two different cities in each country are studied to give a clear representation of the feasibility of these systems. Table I lists the horizontal and in-plane irradiation at each of the selected locations.

TABLE II
FEASIBILITY MODEL INPUT DATA

Location:	San Francisco, US	Chicago, US	Guangzhou, China	Xi'an, China
Technical Submodel				
EV Battery Capacity (kWh) [11]		30		
EV Charging Power (kW) [11]		6.6		
EV Energy Consumption (kWh/km) [11]		0.174		
ICEV Efficiency (L/km) [12]		0.072		
Average driving distance (km/day) [13][14]	26	32	28	26
Avg. in-plane irradiation (kWh/m^2*year) [10]	2110	1640	1490	1580
Yearly PV Degradation Rate [15]		0.5%		
Economic Submodel				
Base Fuel Price (USD/L) [16][17]	0.99	0.82	1.03	1.03
Electricity Price (USD/kWh) [18]-[20]	0.26	0.05	0.07	0.07
Sellback Rate* (USD/kWh) [21]-[23]	0.03	0	0.03	0.03
PV Cost (USD/kW$_p$) [24][25]	1280	1280	1010	1010
Storage Cost (USD/kWh) [26]	990	990	990	990
Discount Rate		5%		
Environmental Submodel				
Grid Footprint (g CO_2-eq/kWh) [27][28]	239	577	910	1180
PV Footprint (g CO_2-eq/kWh) [29]	21	26	26	26
WTW Gasoline Footprint (g CO_2-eq/km) [30]		178		
Storage Footprint (g CO_2-eq/Wh) [31]		110		
Project Lifetime (years)		10		

*Surplus compensation for net metering schemes in U.S. locations, feed-in tariff in Chinese locations.

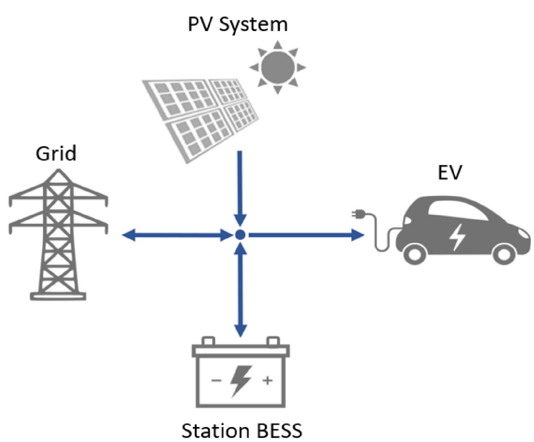

Fig. 1. System configuration for a PV-powered EV charging station with local energy storage.

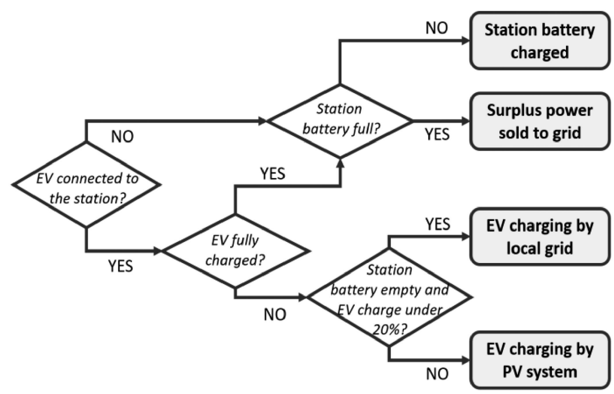

Fig. 2. Charging algorithm flowchart used in the EV feasibility model.

II. METHOD

A. EV Feasibility Model

A feasibility model has been previously developed by the authors to analyze the interactions between a PV system, an EV and the local grid (with the possibility of adding a local battery storage system, see Fig. 1) in order to determine the system's global energy balance, yearly cash flows and cumulative emissions within a specific time frame. In addition to the PV vehicle charging system, a grid-charged EV and a gasoline-fueled ICEV are also modeled as [8].

The model assumes EV properties similar to those of a Nissan Leaf, which is used for commuting during weekdays, traveling a given distance during a fixed time span. In order to match the times at which PV production takes place, the charging system is assumed to be a silicon PV system installed in commercial or office parking lots where users park and charge their vehicle during working hours (9:00 A.M.–5:00 P.M.). The charging point operates at 6.6 kW (see Table II) corresponding to a Level 2 charger.

PVGIS datasets with hourly solar irradiance values for a period of one year are used as the main input for estimating PV production, followed by an estimation of the hourly state of charge for the EV and the BESS as well as the system's expected exchange with the grid. Regarding the station's charging operation, electricity is stored in the charging station's stationary battery (BESS) whenever the PV system produces electricity and the EV is either not plugged in or the car's battery is fully charged, as shown in Fig. 2. Grid charging only occurs if the stationary battery is depleted and the car's battery reaches a depth of discharge of 80%. A mathematical description of this

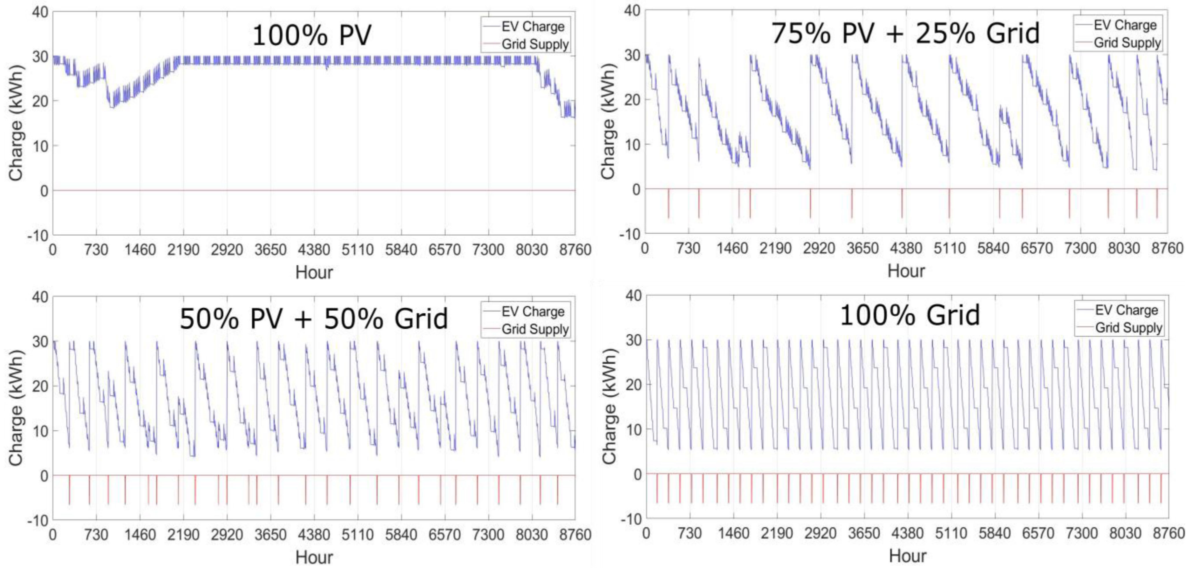

Fig. 3. Hourly EV charge and grid supply (in kWh) during a one-year period in San Francisco for each modeled scenario (5-kWh BESS).

TABLE III
NUMBER OF GRID CHARGING EVENTS

Location	100% PV	75% PV + 25% Grid	50% PV + 50% Grid	100% Grid
San Francisco	0	14	26	43
Chicago	0	16	32	52
Guangzhou	0	17	28	57
Xi'an	0	17	25	43

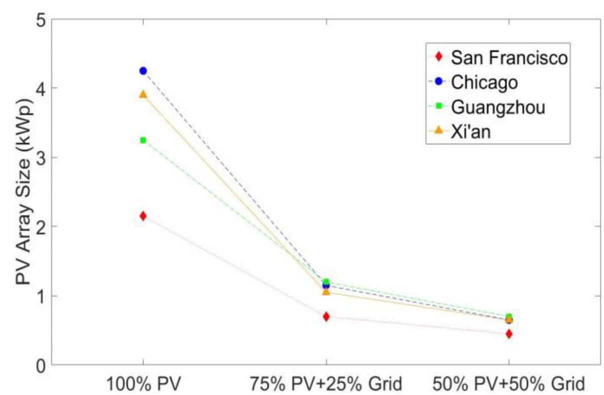

Fig. 4. Array size required to meet the PV share set by each scenario for a system with a 5-kWh BESS.

charging algorithm is presented in full detail in our previous work [8]. A charging efficiency of 90% is assumed for both the BESS and the EV battery; grid charging efficiency is also estimated at 90%.

Economic and environmental indicators are calculated based on this energy balance. The economic analysis calculates an annual cash flow based on investment costs for the PV array and the station BESS, grid purchases, and revenue from grid sales. Avoided fuel costs from an equivalent ICEV are also considered a revenue stream in this model; a linear fuel price increase of 6% per year is forecasted in line with historical trends in crude oil prices [32]. The environmental analysis, on the other hand, takes into account the lifetime emissions of the storage system based on its total capacity, whereas the PV and grid emissions are estimated on a kWh basis.

The outputs for the economic and environmental feasibility analysis are also combined to calculate the system's greenhouse gas (GHG) mitigation cost. This indicator is frequently used to compare different strategies for GHG emissions reduction [1], [33], and is defined as the net cost of an emissions reduction measure divided by the amount of emissions avoided (units: USD/ton CO_2-eq).

B. Input Data

Table II lists the main inputs used by the feasibility model in each of the four selected locations. Four different scenarios are modeled to evaluate the feasibility of a PV charging system at each location, based on different PV/grid energy shares over a year. These scenarios are as follows.

1) *100% PV*: All charging electricity originates from the PV system; excess generation is exported to the grid.
2) *75% PV + 25% Grid*: 75% of the annual charging electricity is supplied by the PV system and 25% is supplied by the grid.
3) *50% PV + 50% Grid*: 50% of the annual charging electricity is produced by the PV system and 50% from the grid.
4) *100% Grid*: The EV is only charged by electricity from the grid.

III. RESULTS

Fig. 3 shows the hourly EV charge and grid supply (in kWh) in all four scenarios for a system located in San Francisco. It can be observed that a lower PV share correlates with an increased number of battery charging cycles, particularly cycles

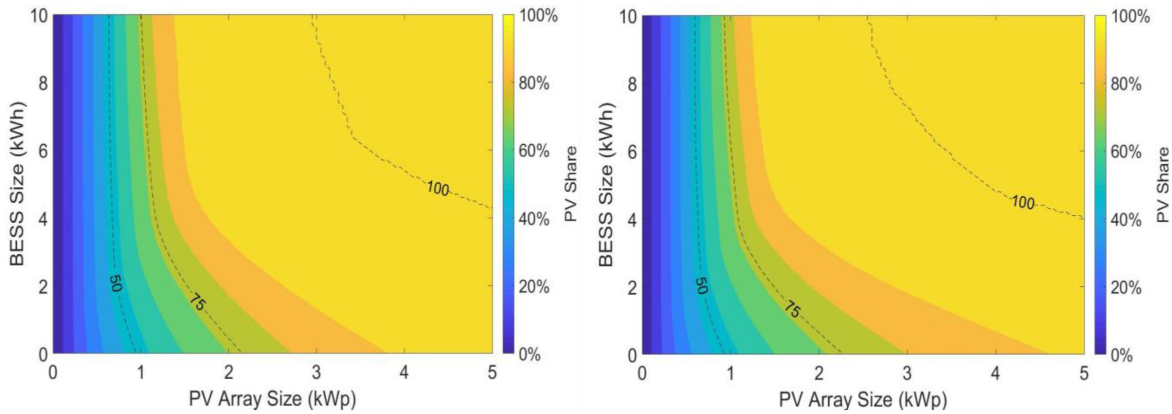

Fig. 5. Technical evaluation: Contour plots of a charging system located in Chicago (left) and Xi'an (right) showing dotted lines with a constant PV share of 50%, 75%, and 100%.

involving deep discharging; this is expected to decrease EV battery lifetime, showing an additional benefit of EV charging in high-share solar power scenarios. Additionally, it is possible to see how the number of grid charging events (corresponding to peaks in the grid supply curve) decreases as the PV share increases, with the 50% and 75% PV scenarios drawing power from the grid only 14 and 26 times, respectively, as opposed to the 43 grid charging events required in the grid-only charging scenario. This decrease follows a seasonal pattern as well, as the density of charging events in the summer months is slightly lower than that of the winter months.

This analysis was done in all four locations to show the system's various interactions with the grid depending on each scenario. The required grid charging events for all four locations are shown in Table III.

A. Technical Feasibility

The PV array size required to meet the share of PV electricity set by each scenario is shown in Fig. 4. It can be seen that for the set BESS capacity (5 kWh), a 100% PV share can be achieved in all locations with less than 5 $\mathrm{kW_p}$ of PV capacity. The required capacity roughly correlates with in-plane irradiation at each location with Chicago requiring the largest system (4.3 $\mathrm{kW_p}$) and San Francisco the smallest (2.2 $\mathrm{kW_p}$). The difference in array size becomes significantly smaller for lower PV shares with three locations requiring virtually the same PV capacity for the 75% and 50% PV scenarios.

Fig. 5 shows the results for charging systems in Chicago and Xi'an as a function of PV and BESS size where in both cases installing just 1 $\mathrm{kW_p}$ of PV capacity yields shares higher than 50% regardless of which BESS size is used; storage capacity only has a significant impact for achieving PV shares larger than 75%.

B. Economic Feasibility

Fig. 6 shows the results of the economic evaluation of a PV charging system with 5 kWh storage at each location over a period of ten years. In all locations, the highest net present

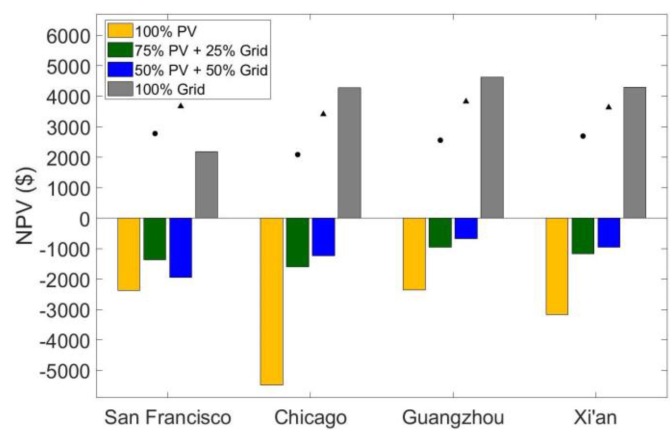

Fig. 6. NPV after ten years for a system with a 5-kWh BESS located in each of the four analyzed locations; icons denote results for a system with the same PV energy share and no storage.

value (NPV) is obtained with grid-only charging, which is likely because of the high investment costs of the storage system. This is clearly seen in systems with no storage (indicated by icons), which have a higher NPV for the 50% and 75% PV scenarios. For instance, a charging station in Chicago with a 5-kWh BESS has a present value of –1233 USD in a 50% PV + 50% grid scenario, which increases to 3549 USD if the storage system is removed while maintaining the same PV energy share.

The contour plot for a system located in San Francisco presented in Fig. 7 shows that the NPV of a system at this location depends strongly on BESS capacity. Additionally, PV system size reaches an optimum around 0.8 $\mathrm{kW_p}$, which corresponds to the point at which grid imports and exports are equal and maximum revenue is earned according to the net metering scheme used at this location. However, results from a system in Guangzhou (Fig. 7, right) show this is not always the case as NPV only decreases when PV system size is increased; this trend was observed in the other two locations as well. Storage costs still have the largest impact on financial attractiveness at

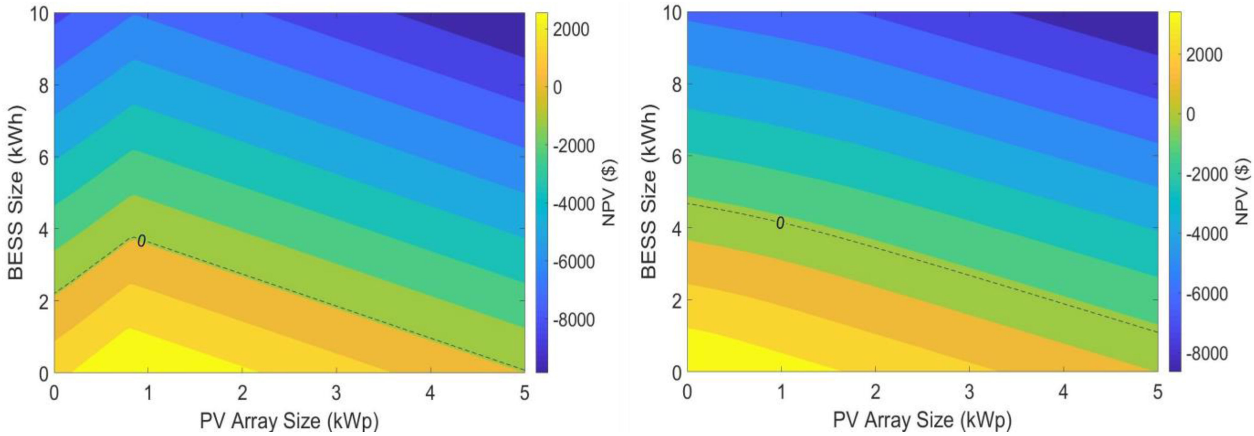

Fig. 7. Economic evaluation: Contour plots of a charging system located in San Francisco (left) and Guangzhou (right) showing the break-even point (NPV = 0) as a dotted line.

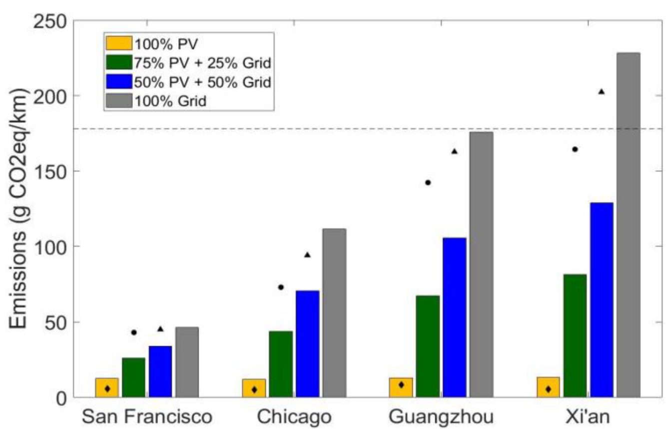

Fig. 8. CO_2-eq emissions per km traveled for a system with a 5-kWh BESS located in each of the four analyzed locations; icons denote results for a system with the same PV share and no storage, whereas the dotted line indicates the emissions per km traveled of a gasoline ICEV (178 g CO2-eq/km).

this location, with a break-even point reached only at BESS capacities lower than 5 kWh.

C. Environmental Feasibility

The emissions per km traveled for each scenario seen in Fig. 8 show that for 100% PV scenarios emissions can be as low as 12–13 g CO_2-eq per km traveled. Results also show that in all locations the grid-only scenario has the highest CO_2 emissions with grid-charged EVs in Guangzhou (175 g CO_2-eq/km) and Xi'an (228 g CO_2-eq/km) potentially emitting an equal or higher amount of CO_2 than an ICEV (178 g CO_2-eq/km). Fig. 9 reinforces this point further, showing that a system in Xi'an requires a PV array of at least 0.5 kW_p to have a lower environmental impact than an ICEV, whereas a system in San Francisco (which has a significantly less CO_2-intensive grid) will emit less than 50 g CO_2-eq/km in almost all cases. In addition to the impact of the grid mix at each location, it can be seen that despite increasing total system costs, the use of local energy storage reduces total emissions for systems with 50% and 75% PV shares (see Fig. 8); this can be attributed to the avoided emissions from reduced grid purchases being greater than the life cycle emissions from the added storage system.

D. GHG Mitigation Costs

Table IV lists the GHG mitigation costs in each scenario for systems with and without local energy storage; as was the case before, an equivalent ICEV is used as a reference for calculating the emissions reduction. It is important to mention that mitigation costs could not be calculated for all scenarios as in some cases PV-powered charging was found to be less feasible, whereas in others a reduction in emissions was not observed.

Overall, PV charging scenarios with local storage have mitigation costs in the order of 120–400 USD/ton CO_2-eq, whereas grid-only charging scenarios have a negative mitigation cost. All systems without local storage have negative mitigation costs as well, meaning that they are "no-regret" options where it is possible to achieve a net reduction in both CO_2 emissions and system cost at the same time.

IV. Discussion

The presented results show the importance of an interdisciplinary analysis of emerging technologies like PV charging stations since there are instances in which an improvement in one aspect of the system is detrimental to another one, setting up a tradeoff between both aspects, which needs to be resolved. In general, it was found that PV charging of EVs can be a feasible solution in all four locations by achieving significant CO_2 emissions reductions at a relatively low cost using systems with modest PV and storage capacities. The charging stations modeled in four Chinese and American cities had comparable sizes and costs, although there was a more significant difference in environmental performance because of the grid energy mix at each location. Table V presents an overview of the feasibility model results for each location.

The technical submodel results show that 50% and 75% PV shares are achievable in all locations with PV array sizes in the order of 1–1.5 kW_p, whereas the 100% PV condition is harder to meet but still possible; this is consistent with our findings for

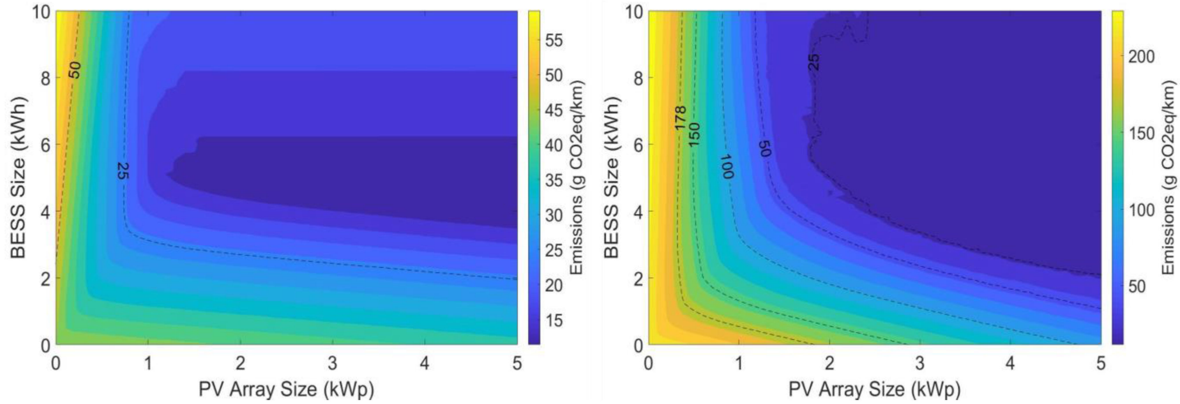

Fig. 9. Environmental evaluation: Contour plots of a charging system located in San Francisco (left) and Xi'an (right) showing dotted lines with constant emissions of 25, 50, 100, and 150 g CO_2-eq/km as well as the average emissions of an equivalent ICEV (178 g CO_2-eq/km).

TABLE IV
SYSTEM GHG MITIGATION COSTS (USD/TON CO_2-EQ)

Scenario:		San Francisco, US	Chicago, US	Guangzhou, China	Xi'an, China
5 kWh Storage	100% PV	212	396	196	284
	75% PV + 25% Grid	131	142	118	179
	50% PV + 50% Grid	199	134	126	288
	100% Grid	-243	-771	*	*
No Storage	100% PV	-	-	-	-
	75% PV + 25% Grid	-303	-236	-980	-3170
	50% PV + 50% Grid	-407	-506	-3418	*
	100% Grid	-243	-771	*	*

- These scenarios required more than 20-kW_p PV capacity and were thus considered technically unfeasible.
∗ GHG mitigation costs cannot be calculated for these scenarios since there was not a reduction in driving CO_2 emissions compared with an ICEV.

similar systems in The Netherlands, Brazil, and Australia [8]. The 100% PV scenario was found to be unfeasible in systems with no local storage, showing that the presence of a BESS is required for fully PV-powered EV charging stations. Additionally, results were found to be sensitive to driving distance, which is the main factor determining total EV demand; for a sensitivity analysis on the model's response to this and other factors such as the EV battery size and yearly solar irradiation please refer to our previous publication [8]. The assumed driving distances are in some cases based on the Euclidean ("as the crow flies") distance rather than on the actual network distance, which is higher by definition and can vary depending on the location [34].

Despite the observed reduction in system emissions, the financial analysis on most PV charging cases yielded a negative NPV at the end of a ten-year period; this was particularly the case for systems relying entirely on PV electricity since they sell a significant amount of surplus energy to the local grid but only receive a small compensation for it. Storage costs represent a significant share of the total system costs but, while decreasing the size of the BESS or removing it altogether can reduce investment costs, it results in a lower PV share and an increase in total emissions creating a tradeoff between sustainability and cost effectiveness. A possible solution to this tradeoff is installing only a small storage capacity (<5 kWh) so that a sufficiently high PV share is achieved while keeping investment costs reasonably low. Furthermore, it is worth mentioning that lithium-ion cost figures from 2017 were considered for the current analysis but are expected to decrease further as this technology continues to mature, increasing the financial attractiveness of this type of systems.

The environmental assessment for the grid-only scenario in both Chinese locations highlights the need for coupling EVs with PV in locations with CO_2-intensive electricity production, where EV implementation on its own could result in a net increase in generated emissions. With the exception of these cases, PV charging resulted in emissions reductions of 60%–93% in the USA and 28%–93% in China compared with an equivalent ICEV. These intervals are similar to those previously estimated for similar systems in the Netherlands (38%–91%), Brazil (83%–92%), and Australia (18%–93%) [8].

In order to assess how changes in the carbon footprint of PV systems would impact the results of our model, we carried out a sensitivity analysis comparing the CO_2 emission values from Table II (2–26 g CO_2-eq/kWh) to an additional value quoted from the literature, namely 57 g CO_2-eq/kWh [35]. Results from this analysis indicate that a 170% higher carbon footprint for PV systems mainly has an effect on the emissions of EVs for scenarios with a high share of PV charging such as 75% and 100% PV charging. For scenarios with 25% PV charging these effects are minor, whereas for those with 0% PV charging logically no effect is observed. In the worst case scenarios, for instance in San Francisco, this results in a relative change of 60% corresponding to an increase of only 7 g CO_2-eq/km for an EV at 100% PV charging. For CO_2 emissions in other locations this increase is at most 6 g CO_2-eq/km. The reason for this comparatively small change is that the CO_2 emissions of the total "PV charging of EVs" system are mainly determined by the CO_2 emissions of grid electricity and batteries rather than those of PV systems themselves.

TABLE V
OVERVIEW OF FEASIBILITY ANALYSIS RESULTS

		5 kWh storage			No storage		
Location:	Scenario	PV Capacity (kW_p)	NPV (USD)	Emissions (g CO_2-eq/km)	PV Capacity (kW_p)	NPV (USD)	Emissions (g CO_2-eq/km)
San Francisco, US	100% PV	2.2	-2380	13	-	-	-
	75% PV + 25% Grid	0.7	-1365	26	2	2778	43
	50% PV + 50% Grid	0.5	-1948	34	0.7	3673	45
	100% Grid	0	2177	46	0	2177	46
Chicago, US	100% PV	4.3	-5487	12	-	-	-
	75% PV + 25% Grid	1.2	-1590	44	2.2	2087	73
	50% PV + 50% Grid	0.7	-1233	71	1	3549	94
	100% Grid	0	4280	112	0	4280	112
Guangzhou, China	100% PV	3.3	-2366	13	-	-	-
	75% PV + 25% Grid	1.2	-955	67	2.9	2558	142
	50% PV + 50% Grid	0.7	-669	106	1.1	3828	163
	100% Grid	0	4626	176	0	4626	176
Xi'an, China	100% PV	3.9	-3171	13	-	-	-
	75% PV + 25% Grid	1.1	-1174	81	2.3	2694	164
	50% PV + 50% Grid	0.7	-958	129	1	3634	202
	100% Grid	0	4295	228	0	4295	228

Required PV capacity for 100% PV scenarios without local storage was larger than 20 kW_p in all locations and was therefore determined as not technically feasible.

It is important to note that the CO_2 emissions from grid electricity cover direct emissions only, whereas those for PV systems and gasoline are life cycle values. It is also worth considering that, while grid emissions figures from 2014 to 2015 were used in this study, average grid CO_2 emissions per kWh are expected to decrease in the future as large-scale renewable sources are increasingly added to the energy mix. Furthermore, this evaluation does not consider the EV's production and end-of-life phases. Estimating the impact of these phases on the system's generated emissions through an adequate life cycle analysis would further improve the accuracy of the modeled results.

Regarding the presented GHG mitigation costs, it is important to consider that because of the inherent uncertainty in estimating system costs and emissions, mitigation costs should only be compared based on their order of magnitude [33]. Based on this criterion, it can be concluded that systems with PV charging and energy storage in all locations have roughly equivalent mitigation costs, whereas grid-only charging and systems without local storage invariably result in a negative mitigation cost. Other studies have cited GHG mitigation costs for electric mobility in the range of 300–1100 USD/ton CO_2-eq [1] and 1900–4500 €/ton CO_2-eq [36] but their focus is on the EVs themselves rather than on charging stations.

V. CONCLUSION

The results presented in this study show that with the right combination of BESS and PV array sizes, the use of PV systems in all four analyzed locations can be a feasible EV charging solution from a technical, financial, and environmental perspective in comparison not only with a gasoline-fueled ICEV but also with a grid-charged EV as well.

1) Yearly PV electricity shares of 50% and 75% are achievable in all four locations requiring PV array sizes in the order of 1–1.5 kW_p. Systems with a 100% PV share would require a larger PV system ranging from 2.2 to 4.3 kW_p depending on the location. The use of local storage was found to have a significant impact only for achieving PV shares larger than 75%.
2) Grid-only charging scenarios had the highest NPV in a period of ten years since no investment in a PV system or local storage was needed. In all other cases, the storage cost was observed to have a significantly larger impact than PV costs in the system's economic feasibility. While removing the BESS from the system significantly increases NPV, this comes at the expense of lower self-consumption and an increase in CO_2 emissions.
3) PV charging stations can reduce the CO_2 emissions produced by an EV by 60%–93% in the USA and 28%–93% in China compared with a gasoline-fueled vehicle. This translates to CO_2 footprints as low as 12–13 g CO_2-eq per km traveled in 100% PV scenarios. Grid-only charging in the two Chinese cities on the other hand was found to potentially emit an equal or higher amount of CO_2 than an ICEV because of the CO_2-intensive grid energy mix at these locations.
4) Systems with PV charging and local storage have GHG mitigation costs in the order of 120–400 USD/ton CO_2-eq, whereas grid-only charging scenarios and systems without local storage have a negative mitigation cost, meaning they are "no-regret" options where it is possible to achieve both a reduction in CO_2 emissions and a net financial benefit.

Because of the present scarcity of solar PV charging EV systems, validating these results against real measurements has not been possible; conducting this validation in the future is recommended in order to further support these findings.

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