EVS29 Symposium
Montréal, Québec, Canada, June 19-22, 2016

Multi-objective optimization of an Autobahn BEV charging station supplied by renewable energy

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Summary

In order to address battery electric vehicles' future ability to travel long distance this paper analyzes a sample case study of supra-regional charging, an Autobahn battery electric vehicle (BEV) charging station supplied by renewable energy. A tri-objective optimization of a local renewable energy system demonstrates how the charging station's levelized cost of energy, life cycle emissions and stress on the electric grid can be reduced simultaneously by introducing a combination of partially curtailed photovoltaic generators and a battery electric storage system.

Keywords: optimization, renewable, infrastructure, fast charge

1 Introduction

Schill et al. demonstrated how the introduction of battery electric vehicles (BEV) in Germany increasingly stresses the electric distribution grid and leads to BEV-specific greenhouse gas (GHG)-emissions substantially higher than those of the overall power system, if not complemented by additional renewable energy generation [1]. A local renewable energy charging station must be designed to guarantee the coupling of BEV charging and renewable energy generation so as to both decrease life cycle emissions as well as mitigate stress on and the extension of the electric grid. While storage options play a vital role in the balancing of volatile renewable generation, the idea of "over-installation" of renewable energy in combination with its curtailment has been mentioned in the past as a potential efficient alternative to storage capacity but was left open for further discussion [2].

While current BEV's ranges generally do not allow long distance travels, it is expected that future BEVs will allow ranges of a few hundred kilometers [3], [4], making long distance travels possible, and thus requiring supra-regional charging options, like an Autobahn charging station. In fact, a supra-regional network of single fast charging stations has already been positioned in central Germany to serve the needs of long-range travel [5], [6].

This paper aims at offering a sample case study that addresses the challenges of transforming supra-regional infrastructures to supply BEVs cost-efficiently and sustainably.

2 Methodology

In order to identify how a supra-regional charging station can be supplied with energy sustainably and cost-efficiently while at the same time mitigating stress on the grid, an exemplary renewable energy charging station system supplied by photovoltaic (PV) generators, a battery electric storage system (BESS) and an electric grid as the point of common coupling (PCC) is employed to supply a given electric demand of electric vehicles (see Figure 1). A computer model of the charging station is employed to assess and optimize the system's performance regarding levelized cost of energy (LCOE) minimization, minimization of the maximum power from the grid (P_{max}) and minimization of life cycle emissions (LCE).

Due to the anticipated conflict between these three objectives, the result of optimization is expected to be a three-dimensional optimal pareto curve that identifies the trade-off decision makers should be aware of during the design of the charging station and its components.

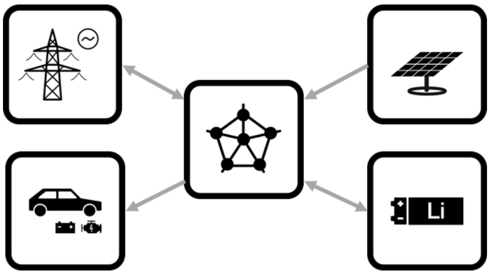

Figure 1: Topology of exemplary charging station

2.1 Simulation model

The simulation model aims at modelling the power flow between the charging station's components. It solves the energy balance with a one hour time resolution over one year to anticipate the system's performance for a planning horizon of 20 years. Data for component parameterization is listed in Table 1.

Table 1: Parameterization of system's components

component	**PV**	**BESS**	**PCC**
economic	$p_{pv} = 1000$ €/kW$_{peak}$ [7], [8]	$p_{bess} = 500$ €/kWh$_{cap}$ [9]	$p_{pcc} = 0.15$ €/kWh$_{el}$, $r_n = 6.7\%/a$ [10]
	$WACC = 7\%$ $Cost_{op} = 1\%/a \cdot Cost_{inv}$		
ecological	$em_{pv} = 800$ kg CO_2eq./ kW$_{peak}$ [11], [12]	$em_{pv} = 69$ kg CO_2eq./ kWh$_{cap}$ [13]	$em_{pcc} = 569$ g CO_2eq./kWh$_{el}$, $r = -1.2\%/a$ [14]
technical	$latitude = 52\,°$, $longitude = 13\,°$, $\alpha = 180\,°$ (S), $\beta = 35\,°$ $\eta_{STC} = 16\%$ (mc-Si) [7]	$r_{sd} = 50\%/a$ $\eta_{in} = 95\%$ $\eta_{out} = 95\%$ $C_{max} = 2^{-h}$ $n_{cyc,nom} = 4000$ [9] $T_{cal} = 10a$ [9]	

To synthesize an electric load curve for the charging of electric vehicles fueling data of a mid-sized gas and diesel fuel station is transformed under the assumption that an equivalent electric charging station would be supplying a BEV fleet with the same amount of "distance travelled" per time unit. While this assumption is neglecting the fact that BEVs storages are not comparable to those of internal combustion engine vehicles, it accounts for the perception of peaks in charging load due to travel behavior that is assumed to be largely technology independent (high during midday and low to zero during the night, see Figure 2). Thus the historical data of fueled gas and diesel volume per time step can be transformed into an electrical charging load through the specific electric energy or fuel required to travel the same distance (0.078 l/km, 0.0681 l/km and 0.2 kWh/km for gasoline, diesel and electric energy respectively [15], [16]).

$$P_{bev}(t) = \frac{\bar{E}_{el}(d)}{\bar{V}_{fuel}(d)} \cdot \dot{V}_{fuel}(t) \tag{1}$$

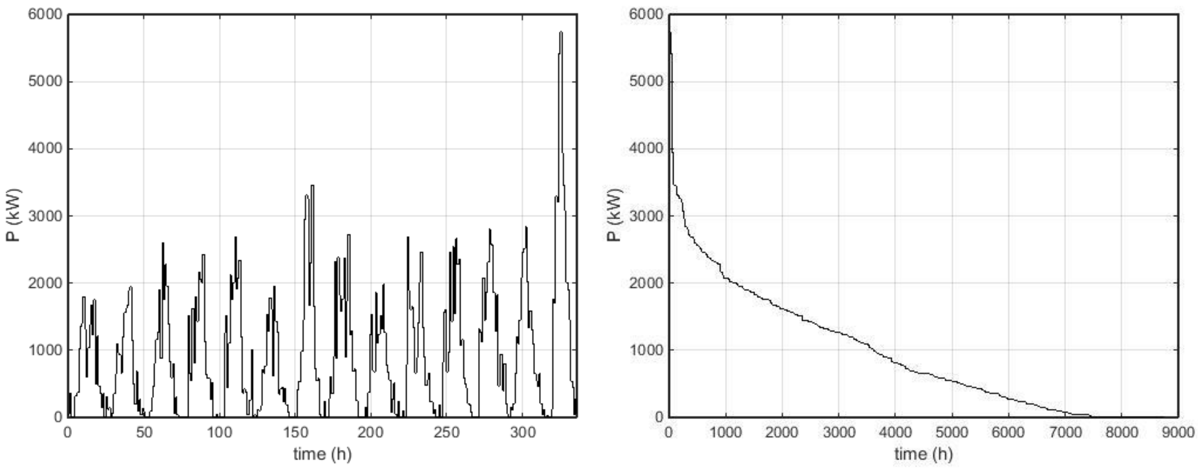

Figure 2: Load curve of BEV charging over two weeks (left) and as load duration curve (right)

The electric energy supplied by the PV generator is simulated using a comprehensive PV model using measured timeseries for direct and diffuse radiation and considering location, azimuth and elevation angle of the generator surface [17]. Resource data are based on NASA SSE data (Surface Meteorology and Solar Energy SSE Release 6.0) [18]. The original data were converted to hourly resolution by the German Aerospace Center [19]. The simulated PV generators yearly energy yield amounts to 894 kWh/kW$_{peak}$.

Power flow modelling of the BESS is based on energy balancing, taking into account charging and discharging efficiencies as well as the rate of self-discharge in each time step of the simulation. Lifetime of the BESS is determined using the post-processing model of Ah-throughput counting [20], which counts the amount of charge through the BESS. The end-of-life criterion is based on nominal charge throughput.

$$T_{life} = min \quad (T_{cyc}, T_{cal}) \tag{2}$$

$$T_{cyc} = \frac{n_{cyc,nom} \cdot Cap_{bess}}{\sum_{8760h} E_{bess,out}} \tag{3}$$

The charging and discharging of the BESS is guided by few basic rules. If the residual load is positiv (less PV generation than EV load), the share of power smaller than some threshold value P_{thr} is taken from the grid (see region a in Figure 3). The difference between the residual load and P_{thr} is then discharged from the BESS (b). In times where there is more PV generation than EV load, the energy is charged into the BESS (c) until the maximum SOC is reached, in which case the excess power is discarded (d) by curtailing PV generation. On the one hand this may not seem reasonable from an economic point of view as it decreases the overall yield of renewable energy, on the other hand however it serves the purpose of mitigating stress on the grid. In addition, while the assumption of complete curtailment of excess renewable energy is pessimistic it seems more realistic than complete feed-in of that energy into the grid for high systems penetration rates of renewable energy technologies.

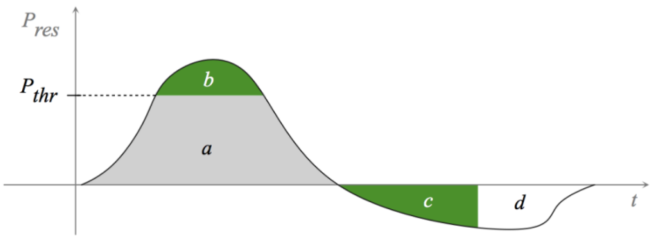

Figure 3: Operational heuristic of BESS charging and discharging

The point of common coupling is where the system's power flow balance is solved for each time step of the simulation and describes the power flow that is necessary to be provided by the grid.

$$P_{pcc}(t) = P_{pv}(t) + P_{bess}(t) - P_{bev}(t) \tag{4}$$

2.2 Optimization approach via key performance indicators

Optimization was conducted using RLI's multi-objective evolutionary algorithm [21] with the aim of simultaneously and equitably minimizing the key performance indicators of LCE, LCOE and P_{max} by determining the optimal combinations of the two major topology design parameters of Cap_{pv} (in kW_{peak}) and Cap_{bess} (in kWh) as well as the operational design parameter of P_{thr} (in kW). Optimization is executed with a population size of 300 over 100 generations. The design parameters' values can range between 0 and 100,000 kW or kWh with a granularity of 10 kW or kWh.

2.2.1 Life cycle emissions (LCE)

Life cycle emissions consider all GHG-emissions associated with the production, installation, operation and recycling of the charging station's components that are part of the optimization process.

$$LCE = \frac{\sum_i (\sum^{20a} Em_{fix} + \sum^{20a} Em_{var})_i}{\sum^{20a} E_{bev}} \tag{5}$$

2.2.2 Levelized cost of energy (LCOE)

Levelized cost of energy in this paper describe the cost per energy unit charged by the BEVs and takes into account all capital and operational expenditures (levelized over all years within the planning horizon) of all components that are part of the optimization process [22].

$$LCOE = \frac{\sum_i An_i}{\sum_{8760h} E_{bev}} \tag{6}$$

2.2.3 Stress on the grid (P_{max})

While the general idea of "stress on the grid" can be defined in many ways (e.g. peak-base-load-ratio or self-sufficiency-rate), the focus in this work lies on the maximum power supplied by or fed into the grid. This is assumed to be particularly suited for a system like a supra-regional charging station as it is directly linked to the extent of a transmission line needed to supply a remote charging station.

$$P_{max} = max_{8760h}\ |P_{pcc}| \tag{7}$$

3 Results

The population of solutions converged against a three dimensional pareto front representing the conflict between the three objectives (see Figure 4). In order to analyse the pareto front and extract useful information for the decision maker each of the two-dimensional projections are cut out and limited to the non-dominated set.

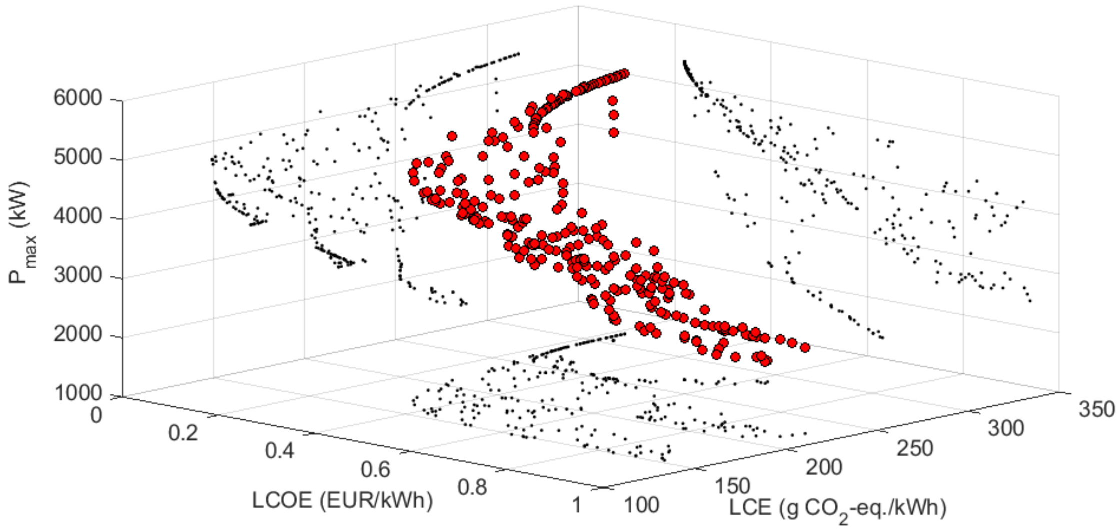

Figure 4: Optimization result, three-dimensional pareto front (red) in objective function space with projections (black)

3.1 LCOE-LCE-trade-off

Optimization results show that a maximum cost reduction of 18% can be achieved by introducing PV to the system. In this case optimization demonstrates how the combination of overcapacity and curtailment of a renewable energy generator is more economic than storing that energy in a BESS for later times. In this case up to 41% of the overall generated PV energy yield are curtailed before a storage is employed (see solution #4 in Figure 5 and Table 2). Minimal LCE with a reduction of about 70% are achieved by a combination of PV and BESS. The results demonstrate the extent of the conflict between the minimization of both LCOE and LCE. Throughout the pareto solution BESS's influence on the overall GHG-emissions is small compared to that of PV and the grid (up to 10% for highest BESS capacity). Optimization of the BESS operation suggests a straightforward approach for the reduction of LCOE and LCE: BESS is being discharged without any threshold.

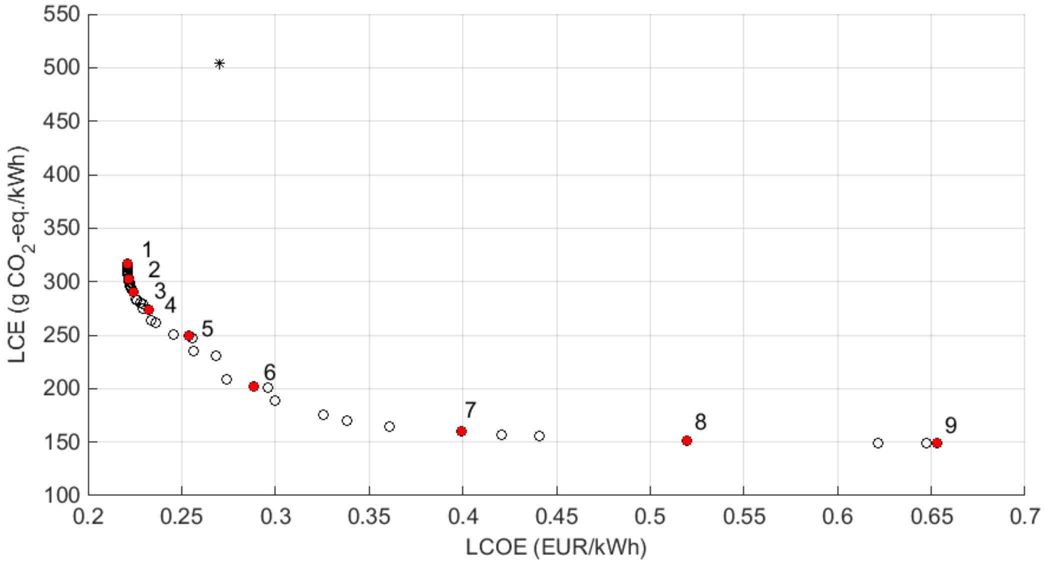

Figure 5: Trade-off curve between LCOE and LCE as well as system with zero PV and BESS capacities (*)

Table 2: Objective values and optimized parameters of selected solutions along pareto front of Figure 5

#	*LCOE*	*LCE*	P_{pv}	Cap_{bess}	P_{thr}	$E_{pv,loss}$	$\varphi_{ghg,\ grid/pv/bess}$
	EUR/kWh	g CO_2-eq./kWh	kW_{peak}	kWh	kW	kWh/kW_{peak}	%
*	0.270	504	0	0	0	0	100/0/0
1	0.221	317	5180	0	0	211	92/8/0
2	0.222	302	6060	0	5350	258	90/10/0
3	0.224	289	6940	0	0	298	89/11/0
4	0.233	273	8730	0	54220	374	85/15/0
5	0.254	249	11480	560	0	442	78/22/0
6	0.288	201	13450	3960	0	429	67/32/1
7	0.399	160	16160	12710	0	442	49/48/3
8	0.520	151	15230	23730	0	402	45/48/7
9	0.653	149	15710	34400	0	407	40/50/10

3.2 LCOE-P_{max}-trade-off

Results show how a cost-efficient reduction in P_{max} can be achieved through a combination of PV and BESS with a peak-focused discharging strategy, with $P_{thr} \approx P_{max}$ for solutions #5 to #9. Maximum reduction in P_{max} of 76% can be achieved only through cost-intensive large capacities of PV and BESS. As was the case with the LCOE-LCE-trade-off, lowest-cost results are achieved through the utilization of curtailed PV power, underlining the importance of curtailment and overcapacity of renewable generation units as supposed to storage technologies.

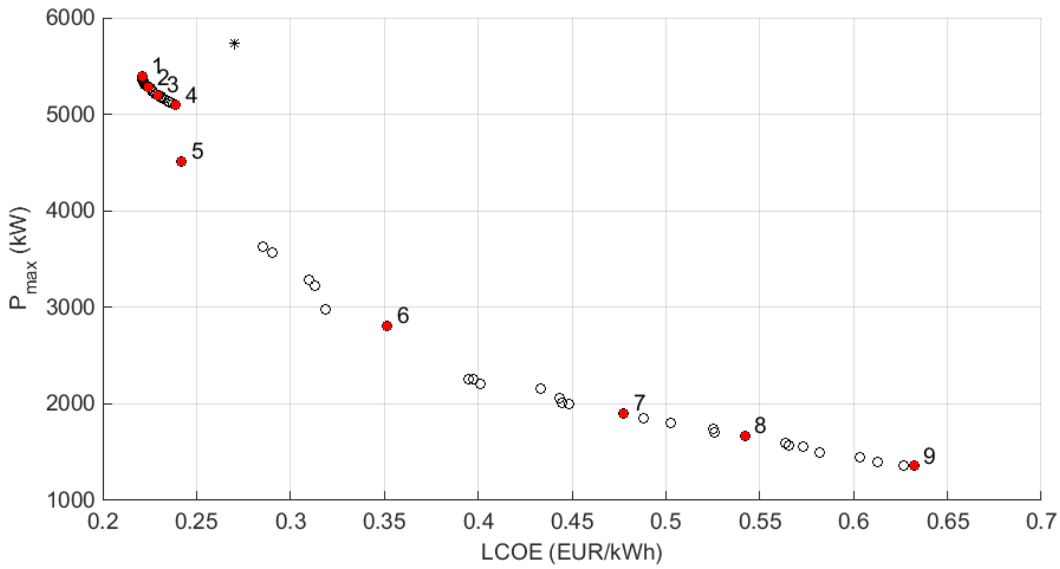

Figure 6: Trade-off curve between LCOE and Pmax as well as system with zero PV and BESS capacities (*)

Table 3: Objective values and selection of optimized parameters of selected solutions along pareto front of Figure 6

#	***LCOE*** EUR/kWh	***P*** ***max*** kW	***P*** ***PV*** kW_{peak}	***Cap*** ***BESS*** kWh	***P*** ***thr*** kW	***E*** ***pv,loss*** kWh/kW_{peak}
*	0.270	5738	0	0	0	0
1	0.221	5395	5180	0	0	211
2	0.224	5279	6940	0	0	298
3	0.229	5201	8120	0	0	351
4	0.239	5095	9710	0	0	406
5	0.242	4510	5880	1680	4510	247
6	0.352	2810	15030	5570	2810	533
7	0.478	1902	21800	10290	1850	621
8	0.542	1670	27810	10110	1670	671
9	0.632	1355	33480	12310	1330	701

3.3 LCE-P_{max}-trade-off

Results show how both LCE and P_{max} can be reduced simultaneously without conflict, as the reduction of both objectives employs some combination of PV and BESS. Ultimate minimization of P_{max} however is not achieved without increasing LCE as it involves larger PV (over-)capacitites as well as a power- instead of an energy-focused utilization of BESS ($P_{thr} \neq 0$ for solutions #8-10).

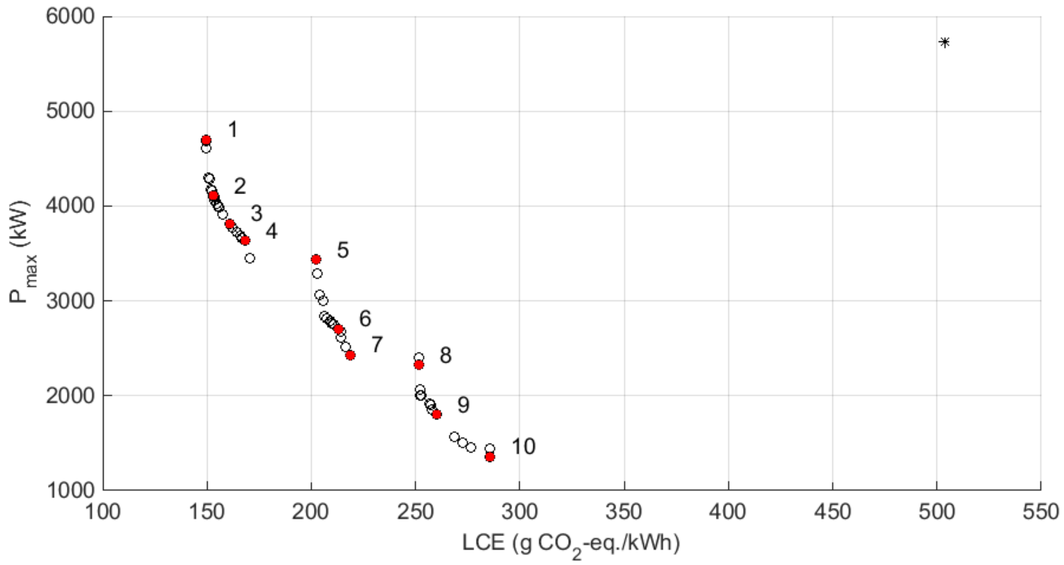

Figure 7: Trade-off curve between LCE and Pmax as well as system with zero PV and BESS capacities (*)

Table 4: Objective values and selection of optimized parameters of selected solutions along pareto front of Figure 7

	LCE	P_{max}	P_{PV}	Cap_{BESS}	P_{thr}
#	g CO_2-eq./kWh	kW	kW_{peak}	kWh	kW
*	504	5738	0	0	0
1	149	4698	15710	34400	0
2	152	4110	21160	38710	0
3	161	3813	25010	45940	0
4	168	3633	27350	42740	0
5	202	3436	36680	25490	0
6	212	2705	39410	25490	0
7	218	2430	38010	72880	0
8	251	2322	16890	11230	2000
9	260	1800	23040	11200	1800
10	285	1355	33480	12310	1330

4 Discussion and résumé

It can be expected that deployment of supra-regional charging stations for BEVs will lead to additional demand loads with high peaks during midday. Under the assumptions used in this paper it could be shown how utilizing some optimally designed combination of PV and BESS can reduce the system's LCE by up to 70%, LCOE by up to18% and P_{max} by up to 76% compared to a simple grid connection of the charging station. However not all three key performance indicators can be minimized simultaneously because they are at least partially conflicting. While PV generators alone can help reduce both LCOE as well as LCE considerably, BESS is needed for the reduction of P_{max}. It could be shown that oversizing of PV capacitity and the curtailment of some of its energy generated is more cost-efficient even on a local scale than the storing of that energy in a BESS. Although a BESS operating strategy which is focused on the balancing of renewable energy is sufficient for reducing LCOE as well as LCE, it could be shown that ultimate reduction of P_{max} can only be achieved by shifting operation towards the reduction of power peaks, which makes less effective use of the BESS within its lifetime, thus lowering its economic and ecological viability. While ultimate LCE reduction is achieved by large BESS and PV capacities, (increasing LCOE by up to 295% compared to the lowest-cost solution) BESS's influence on the overall GHG-emissions throughout the entire pareto set is small compared to that of PV and the grid.

The exemplary case of an Autobahn BEV charging station shows the objective conflicts decision makers should be aware of when designing renewable energy systems. Further analyses should include additional renewable technologies such as wind power (which could potentially mitigate land use) as well as other electric mobility technologies such as fuel cell electric vehicles for heavy duty mobility purposes. Furthermore the optimization results and the conclusions therefrom should be tested for robustness regarding changes within the set of model assumptions in order to gain further insight into dependencies and uncertainties when designing a BEV charging station supplied by renewable energy.

Acknowledgments

This work was funded by the *German Federal Ministry of Economic Affairs and Energy (BMWi)* within the initiative *Berlin-Brandenburg International Showcase for Electromobility.*

Nomenclature

α	azimuth angle
An	levelized annual cost
β	elevation angle
$bess$	battery electric storage system
bev	battery electric vehicle
C	c-rate for BESS
cal	calendaric
Cap	capacity
$Cost$	cost
cs	charging station
cyc	cyclic
d	distance
E	energy
Em	GHG-emissions
el	electric
fix	fix, depending on component's capacity
$fuel$	fuel, gasoline
i	component
inv	investment
LCE	life cycle emissions
$LCOE$	levelized cost of energy
η	efficiency
n	nominal
op	operational
P	power
pcc	point of common coupling
pv	photovoltaic
r	rate
res	residual, difference between load and generation
sd	self-discharge
SOC	state of charge
STC	standard test conditions
T	time period
t	time step
thr	threshold
φ	ratio
V	volume
var	variable, depending on component's operation
$WACC$	weighted average cost of capital

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Having graduated from HTW Dresden (Dipl.-Ing.(FH) Automotive Engineering) and HTW Berlin (M.Sc. Renewable Energy Systems) Oliver Arnhold is a founding member of RLI and established its research field on mobility with renewable energy. He works on the integration of alternative vehicle concepts, such as battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV), into renewable energy systems.