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Design of an electric vehicle fast-charging station with integration of renewable energy and storage systems

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A B S T R A C T

The development of electric vehicles (EVs) depends on several factors: the EV's acquisition price, autonomy, the charging process and the charging infrastructure. This paper is focused on the last factor: the design of an EV fast-charging station. In order to improve the profitability of the fast-charging stations and to decrease the high energy demanded from the grid, the station includes renewable generation (wind and photovoltaic) and a storage system. Unlike other papers, this one uses a detailed model of the charging process that considers the arrival time and state of charge of electric vehicles. First, the Monte Carlo method is used to model the EV demand and the renewable generation. Later, a genetic algorithm (GA) optimizes the installation and operation of the EV fast-charging station. It finds the optimal solution that maximizes the profit measured by its net present value (NPV). Several cases are studied to analyse the influence of renewable energies and storage systems. The obtained results show that a mix of renewable energies and storage systems attains the best cost efficient solution.

1. Introduction

In the next few years, the number of electric vehicles (EVs) is expected to increase exponentially, due to the squandering of oil and the environmental impact associated with its use. For that reason, there is a tendency to coordinate efforts to reduce urban pollution and greenhouse gas emissions. At present, one of the most important problems in EV development is the shortage of charging infrastructure [1]. Drivers can charge their EVs at home, but the charge time is quite long. To promote the EV development, it is necessary to install fast-charging station in which the EV battery can be charged in around 15 min. By contrast, the disadvantage of fast charging is the high power demand and its impact on the grid. In order to address this, renewable sources and storage systems can be installed in these stations [2]. Review of studies about the appropriate system design for an EV station's installation and its operation can found in [3–9].

Several authors have analysed the impact of EV station operation within the electrical network. They present different methods to level the load curve. Xu et al. [10] showed a coordinate charging strategy to improve the effects of EV charging in the electrical demand curve as well as the profit of the EV stations. Zhang and Qian [11] presented a methodology to charge EVs during night time. Cao et al. [12] proposed an intelligent charging method for EV in response to time-of-use price that alleviates the stress in the network during the peak periods. Fazelpour et al. [13] developed an algorithm with two phases to integrate smart parking with a plug-in hybrid EV. First, the algorithm optimizes the size and location of renewable energy installations through the grid. Then, it optimizes the characteristics of EV charging. This reduces the power losses and improves the voltage profile in the network.

Some papers address the problem of locations for these EV stations and even their sizing but with simplifications about their demand and operation. Sadeghi-Barzani et al. [14] used a mixed integer non-linear optimization approach to locate fast-charging stations in a city; they considered the development and electrification costs, EV energy loss, and electric grid loss as objectives. In the model, they only defined the number of EVs arriving at the station, but they did not consider the arrival time or the occupation of the station. Wang et al. [15] presented a multiobjective planning model for EV charging stations to reduce power losses and voltage deviations in the distribution system. They considered a fixed demand and did not consider the operation of the charging process. Sungwoo and Kwasinski [16] used a spatial and temporal model of EV charging demand to locate the EV station. They used a fluid dynamic traffic model and queueing theory. Xiang et al. [17] developed a model to determine the siting and sizing of charging stations. They considered the interactions with the electrical grid, but they did not consider other types of energy sources.

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Nomenclature

$Cbuy_h$	buy price at electrical market at hour *h* (€)
Cch	cost of a charger (€)
Cm_t	maintenance cost of storage system at year *t* (€/year).
Cpv	square meter cost of photovoltaic panels (€/m^2)
$Cr\&m_t$	replace and maintenance of storage system at year *t* (€)
$Csale_h$	sale price at electrical market at hour *h* (€)
Cs_h	energy price station at hour *h* (€)
$Csto$	cost of storage system (€/kWh)
Cw_k	cost of the wind generator *k* (€)
$ECsto_h$	energy charged from storage system at hour *h* (kWh)
$EDsto_h$	energy discharged from storage system at hour *h* (kWh)
Eev_h	energy supplied to *EV* customers at hour *h* (kWh)
$Eg2s_h$	energy consumed from grid at hour *h* (kWh)
$EMAXev_h$	maximum energy demanded by *EV* customers at hour *h* (kWh)
Eph_h	energy supplied by photovoltaic generators at hour *h* (kWh)
$Es2g_h$	energy supplied to grid at hour *h* (kWh)
$Esoc_h$	energy level in storage system at hour *h* (kWh)
$Esoc_{h-1}$	energy level in storage system at hour $h-1$ (kWh)
$Esto_{inst}$	nominal energy capacity of the installed storage system (kWh)
$ETHsto_k$	total energy throughput of battery *k* that is equal to the life cycle by battery capacity (kWh)
Ew_h	energy supplied by wind generators at hour *h* (kWh)
h	an hour index
I	initial investment (€)
i	interest rate
$INFLOW_h$	cash inflow (income) at hour *h* (€)
n	the number of years considered in the study (year)
NCF_t	net cash flow at year *t* (€)
NPV	net present value (€)
nw	the number of types of wind generators considered in the study
$OUTFLOW_h$	cash outflow (expenses) at hour *h* (€)
Pch_{inst}	rated power of the EV fast-charging supplier (kW)
$PCsto_h$	power of charge for storage system at hour *h* (kW)
$PDsto_h$	power of discharge for the storage system at hour *h* (kW)
Pev_h	power of the EV fast-charging supplier at hour *h* (kW)
$Pg2s_h$	power consumed from grid at hour *h* (kW)
Pgc_{max}	power limit in the grid connexion point (kW)
Pph_h	power supplied for photovoltaic generator at hour *h* (kW)
Pph_{inst}	rated power of the installed photovoltaic generator (kW)
$Ps2g_h$	power supplied to grid at hour *h* (kW)
$Psto_{inst}$	rated power of the installed storage system (kW)
Pw_h	power supplied for wind generator at hour *h* (kW)
Pw_{inst}	rated power of the installed wind generator (kW)
Qch	number of chargers installed
Qw_k	number of wind generators of type *k*
SOC	state of charge of the battery (p.u.)
SOC_{min}	minimum state of charge of the battery (p.u.)
Spv_{inst}	surface installed of photovoltaic panels (m^2)
t	a year index
tev_k	waiting time for each vehicle (min)
tev_{max}	maximum waiting time; 0 (min), in our case
y_k	binary decision variable

A few authors have developed models for the design of EV charging stations, in which they used several simplifications in the design. Vermaak et al. [18] developed a model to calculate the size of a charging station with renewable energy, but the demand is constant and it has no connection to the grid. They optimized the results with Homer software. Hafez et al. [19] presented the optimal design of an EV charging station to minimize the lifecycle cost. They considered renewable energy, connexion to the grid and batteries, but they did not consider the arrival time; the optimization was also done with Homer software. Fathabadi [20] showed the electronic design of an EV charging station with PV and wind generators, but they did not determine the size of the EV station. He focused on the design of the converters and control algorithm. He used a daily curve to model demand, PV and wind generation.

In designs of EV charging stations, the demand models used have been very simple, with constant demand [18] and load profile [19,20]. These load profiles do not consider when the charging of each vehicle begins and ends; rather, they are only an average value for each hour. More complex models exist the operation of EV charging stations. Bae and Kwasinski [21] used a model based on an M/M/s queueing theory, based on the state-transition algorithm used in Shrestha and Hansen [22]. Zhou and Liu [23] use an M/M/s queue based on a cell-transmission traffic model, and Viswanathan et al. [24] used real-world traffic data.

The energy management systems used in the designs of EV charging stations are also very simple. In [18], Vermaak et al. prioritized the charging of the EV and used a battery pack to store energy form renewable sources when there are no vehicles in the station. A similar form of management is used by Hafez et al. [19], but they also included a thermal load that feeds when there is excess renewable energy generation. In [20], Fathabadi developed a MPPT technique to track the maximum power points of PV and wind systems. Other, more complex methods have been found for operating EV charging stations. Authors seek to achieve different objectives in the EV charging process, including to maximize profits [25–27], minimize total energy costs for users [28–32], reduce power losses in the network [31,33], minimize the generation costs [34,35], minimize the peak load [36], avoid congestion in the distribution network [37] or regulate the frequency [38].

Most of the previous papers are focussed on the operations or the impact on the grid, while only a few papers address the design of EV charging stations. Among the papers about design, they do not consider the charging dynamic (the arrival time and state of charge of each electric vehicle) because they have to adapt the input data into an optimization program such as Homer that is not built to solve this kind of problem.

The originality of this paper is as follows:

– The study focusses on an EV charging station design problem with characteristics of an EV charging station operation problem.
– EV power demand is represented by an Erlang B queuing model, which until now has only been used in papers that discuss the optimization of EV operations.
– The EV operations include the purchase and sale of energy in the electricity market, which until now has only been used in papers that discuss the optimization of EV operations.
– This design problem includes a wide variety of energy sources: renewable generators, the grid and batteries.
– A genetic algorithm was adapted to deal with the complexity of the design problem.

The rest of the paper is organized as follows. The mathematical modelling of the optimization problem to design the EV station is explained in detail in Section 2. The probabilistic input data are described in Section 3. Then, the genetic algorithm's characteristics are shown in Section 4. Finally, three cases are studied and compared to show the changes in the design in Section 5, and Section 6 concludes the paper.