Charging of Electric Vehicles and Demand Response Management in a Singaporean Car Park

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***Abstract*—Uncontrolled charging of electric vehicles can affect the power system operation and stability. In cities with high population density and with short driving distances like Singapore, car parks bear a high proportion of private vehicles most of the day. These car parks can be regarded as aggregators and control the charging process. Demand response could be used by the car park operators as an additional source of revenue and thus help offset the high installation costs. This paper investigates different charging strategies and demand response management possibilities within a specific car park. Data for arrival times and parking durations are obtained using available statistical information, charging of individual electric vehicles is controlled by the car park operator and effects of demand response management on the total charging cost of the system is analysed.**

***Index Terms*—Demand Response, Electric Vehicles, Energy Management.**

I. Introduction

Electric vehicles (EV) are expected to play an important role in the future power system. Introduction of EVs would result in new opportunities for car park operators, electricity could be provided to EV when they stay at car parks. Liberalized markets allow operators to either buy energy from a retailer or become a contestable consumer and participate directly on wholesale electricity markets.

In 2006, the interruptible load (IL) programme was introduced by the Energy Market Authority (EMA) to promote competition in the National Electricity Market of Singapore (NEMS). This programme allows consumers to participate in the reserve market by bidding their loads and the corresponding interruptible capacity as reserve, the load is automatically disconnected during emergencies by means of an under-frequency relay. Consumers receive payments based on the reserve price and no additional incentive is paid when the load is curtailed [1].

Demand response (DR) in the energy market will be implemented in 2015 [2]. Under this programme, contestable consumers adjust their electricity usage in response to real-time price signals. Consumers bid into the market the total load of the registered facility for the period together with the proposed energy curtailment and the price threshold. These bids are considered in the Market Clearing Engine (MCE). The MCE is run twice. First, the baseline is obtained using the original demand bid value. Then, the MCE is run again but considering the load curtailment. The load provider will receive an incentive based on the additional consumer surplus generated by reduction on the wholesale electricity price [2]. A price floor is implemented for the DR programme. Load curtailments are only considered if the electricity price is higher than 1.5 times the Balanced Vesting Price (BVP). "This measure prevent load providers to submit very low bids for reductions of load that would have occurred anyway under business-as-usual circumstances" [3].

Extensive literature exists regarding smart charging of electric vehicles. Charging of electric vehicles in residential areas is considered in [4]–[6]. Demand response management (DRM) is considered in [4], [7]. Reference [4] contemplates DRM for EV connected at residential locations. In [7], the authors study power system frequency support using EV charging as responsive demand. Special focus is put on shifting the charging to midnight and early morning periods. Limited range results in EV to require charging not only during non-peak or low-price periods. Charging during peak periods is necessary for drivers parking their vehicles at work or performing leisure activities during the day. Vehicle-to-Grid (V2G) is studied in [8]–[11]. V2G is a very interesting idea but technical requirements that result on higher investment costs for car park operators and consumers concerns regarding battery lifetime may be viewed as challenges for its implementation. Impact and charging management of the EV fleet as a whole is considered in [5], [10], [11]. In [12] and [11], the authors propose a smart charging algorithms while considering the battery constrains but results are aggregated over the total EV population. Whole fleet management involves high technical challenges and may be hard to achieve in reality. Most countries have very strict anti-monopoly laws that will prevent a single entity to manage charging for all the EV connected to the power system. In cities with high population density like Singapore, a high proportion of EV would be located at car parks near shopping malls and offices buildings. A high number of EV charging at the same location may result in overload of the distribution networks. Implementation of smart charging algorithms in car parks would be relatively easier from both the logistic and technical point of view. Additionally, charging management within the car park would ensure that distribution network limits are not exceeded.

This work studies the effect of smart charging for EV in a specific car park and the possible revenues operators could receive by implementing demand response programmes. Due to lower investment cost and technical requirements, only Grid-to-Vehicle (G2V) is considered. An arrival time and parking duration model for a car park is derived using statistical data. A combination of normal and Weibull distributions is used to simulate EV driving patterns (travel distances, time of arrival and parking durations). The car park operator controls the charging process based on the availability and the requirements for each EV. The charging level for each car is obtained by solving a linear optimisation problem. Different case studies are developed using real energy price data from the EMA. For the base case, the optimal charging strategy is obtained by minimizing the total charging cost of the system. The second case considers participation in the reserve market as interruptible load. The last case study possible revenues for participation in the demand response programme.

Section II presents the arrival-departure model for the car park and compares the results to real data from a Singaporean car park. Section III introduces the variables and constrains used in the optimisation problem. Results are shown in Section IV and the conclusions are given in Section V.

II. Car Park Model

A. Arrival-Departure Model

In this work, special focus is put on studying possible revenues for commercial car parks located in non-residential areas near to the city centre. In these car parks, a high proportion of the drivers stay for work or leisure related activities. Fig. 1 shows occupancy values for a typical week in three different car parks located in the city centre area. The occupancies for all three car parks vary considerably when compared against each other but are very similar when comparing different weekdays within the same car park.

Probabilistic modelling is used to create arrivals and parking durations based on the driver profiles. Three different profiles are used and sub-categories are formed based on the finite automaton presented in [13]. The profile *"work"* is used for people working normal hours, different sub-profiles are used to model people arriving earlier and going for lunch breaks at midday. The profile *"leisure"* is assigned to people arriving during the day and staying for leisure related activities. The profile *"others"* is used to model drivers that do not match the profiles *work* or *leisure*. The parameters for the probability functions are derived from the data on [13]. The arrival-departure model is obtained by combining these different profiles. The EV is assumed as available for charging at the beginning of the next period after arrival and up to the end of the last full period before departure.

B. Electric Vehicles Specifications

Based on the vehicle models from the EV test-bed that was launched in June 2011 by the Singaporean government, three types of EV are considered: Mitsubishi i-MiEV, Nissan Leaf and Renault Fluence Z.E.. The total car population is assumed to be uniformly distributed between these three models. The battery capacity and charging limits for the different models are given in Table I.

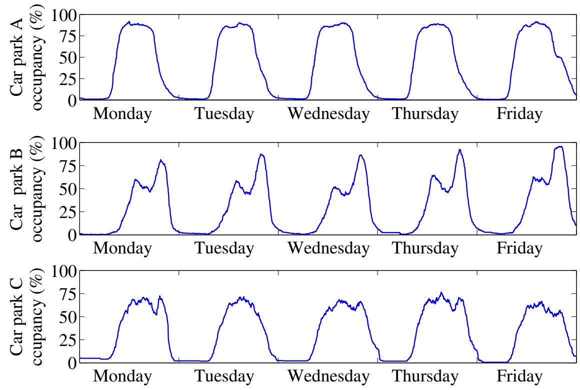

Fig. 1. Occupancy for three car parks at the city centre area

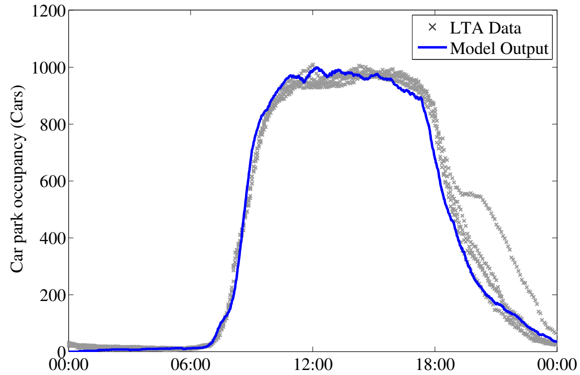

Fig. 2. Model output vs car park data by LTA

Table I
EV Specifications

Car Model	Battery Capacity (kWh)	Max Charging Power (kW)
i-MiEV	16	3.6
Leaf	24	6.6
Fluence Z.E.	24	3.5

C. Initial State of Charge Estimation

In 2012, the average daily distance travelled by private cars was estimated at 50 km [14]. Simulated travel distances are used to obtain the initial State of Charge (SOC) at arrival. A normal distribution with a mean of 25 km and limited between 1 km and 50 km is used. For drivers on lunch breaks with limited travel time, a mean of 5 km and a standard deviation of 1.2 km is assumed. The energy consumption is obtained from [12] and is limited to a range between 15 and 20 kWh/100km.

D. Model Output

The model output is validated against real data obtained from the Land Transport Authority (LTA) of Singapore. Fig. 2 shows the car park model output for a total EV population of 2000 unique cars and 2160 parking events. Fig. 2 shows the model output for a single day compared against the values for car park A in Fig. 1.

III. CAR PARK OPERATION

Participation of the car park in the wholesale energy and reserve market is investigated. In Singapore, buyers and sellers trade energy, reserve and regulation through the Energy Market Company (EMC) in 48 market periods daily. Contestable consumers may purchase energy from the wholesale market and pay the Uniform Singapore Energy Price (USEP). Additionally, consumers may submit load curtailment bids on the energy marker and obtain incentives under the demand response programme or reserve payments by participating in the IL programme [1], [2].

A. Problem Formulation

The objective is to find the least cost solution for charging the EV subject to the output of the car park model, electricity prices, reserve prices, individual EV constrains and car park operator constrains. The problem is formulated using linear programming and both energy and reserve are optimised simultaneously. Cars are charged to a 100% SOC or to the highest possible SOC based on the availability. The total power available for the car park is limited to avoid overloading of the distribution transformers. The EV availability and initial SOC for each EV is obtained from the car park model. A summary of all the sets, parameters and variables is given in Table II.

$$minimize \qquad totalCost \tag{1}$$

$subject\ to$

$$totalCost = \sum_{c\in C}\sum_{m\in M}\{charge(c,m)\cdot d_t \cdot elePrice(m) - varCap(c,m)\cdot d_t\cdot resPrice(m)\} \tag{2}$$

$$\sum_{c\in C} charge(c,m) \leq maxCarpark(m) \qquad \forall\, m\in M \tag{3}$$

$$charge(c,m) \leq limCh(c)\cdot available(c,m) \qquad \forall\, c\in C \text{ and } m\in M \tag{4}$$

$$SOC_r(c) = \sum_{m\in M} charge(c,m)\cdot d_t\cdot SOC_m(c) + SOC_i(c) \qquad \forall\, c\in C \tag{5}$$

$$varCap(c,m) \leq charge(c,m) \qquad \forall\, c\in C \text{ and } m\in M \tag{6}$$

The objective function for the optimisation problem is given in Equation (1). Equation (2) depicts the total cost of the system. Equation (3) constrains the total power drawn from the grid, Equation (4) limits the maximum charging level for the EV and allows charging only when the EV is available, Equation (5) ensures the EV is charged up to the required SOC value and in Equation (6) the variable capacity is limited in relation to the charging level.

An auxiliary variable *"Charging Capacity"* $chCap(c,p,f)$ is introduced to calculate the variable capacity level. The charging energy for each period $p \in M$ is assigned as a variable capacity if the energy for the current period p could be re-scheduled for a future market period f, where $f \in M\{f : f > p\}$. The variable $chCap(c,p,f)$ is included in equations (3) and (4) to prevent constrains violations on the

Table II
OPTIMISATION PROBLEM DATA AND VARIABLES

Indices		
c	-	EV parking events
m	-	Market Period
Sets		
M	-	Market periods
C	-	EV parking events
Constants		
d_t	h	Time duration of each market period
Parameters		
$available(c,m)$	-	Availability for car c at period m
$SOC_i(c)$	%	Initial SOC for car c
$SOC_r(c)$	%	SOC required at departure for car c
$SOC_m(c)$	$\%/kWh$	Conversion factor from charging power to SOC for car c
$limCh(c)$	kW	Maximum charging power for car c
$maxCarpark(m)$	kW	Maximum power level for car c at period m
$elePrice(m)$	SGD/kWh	Electricity price for period m
$resPrice(m)$	SGD/kWh	Reserve price for period m
$DRincentive(m)$	SGD/kWh	Demand response incentive for period m
Variables		
$charge(c,m)$	kW	Charging power for car c at period m
$totalCost$	SGD	Total charging cost for all EV
$varCap(c,m)$	kW	Charging capacity for car c at period m that can be re-scheduled for future charging

* The exchange rate is 1.25SGD/USD as of 22-May-2014

charging limits for the EVs or the car park. The new equations are as follows:

$$\sum_{c \in C} \left[charge(c,m) + \sum_{p \in M} chCap(c,p,m) \right] \leq maxCarpark(m) \quad \forall\, m \in M \tag{7}$$

$$charge(c,m) + chCap(c,p,m) \leq limCh(c) \cdot available(c,m) \quad \forall\, c \in C \text{ and } m,p \in M \tag{8}$$

The variable capacity is set to:

$$\sum_{\substack{f \in M \\ \{f:f>m\}}} chCap(c,m,f) = varCap(c,m) \quad \forall\, c \in C \text{ and } m \in M \tag{9}$$

For market periods when the electricity price is higher than the price floor the operator could submit its bids under the DR programme. The incentive $DRincentive$ is calculated using (10).

$$DRincentive = \frac{1}{3} \cdot USEP_{dif}(m) \cdot sysDem(m) \tag{10}$$

Where the $USEP_{dif}(m)$ is the difference in the electricity price for period m obtained by the market clearing engine with and without load curtailment. The term $sysDem(m)$ is the total energy demand during period m for all the loads buying electricity from the wholesale market. The load provider participating in the DR programme is paid one third of the total consumer surplus generated. Equation (2) becomes:

$$totalCost = \sum_{c \in C} \sum_{m \in M} [charge(c,m) \cdot d_t \cdot elePrice(m) - varCap(c,m) \cdot d_t \{DRincentive(m) + resPrice(m)\}] \tag{11}$$

When the load is scheduled by the MCE, the $charge(c,m)$ for car c during period m must be curtailed and the charging rescheduled to $chCap(c,m,f)$. Contestable costumers can submit load bids simultaneously for both the IL and demand response. The market clearing engine will consider both but at most one will be scheduled. This means that either $resPrice(m)$ or $DRincentive(m)$ will be set to zero depending on which programme the load is scheduled for.

IV. Results

A case study was designed to evaluate how variable electricity prices may affect the total charging cost. Participation in the IL and DR programmes and the effect on the charging cost is investigated. A single day output of the car park model is used and the optimisation problem is run using the electricity and reserve prices for the NEMS during the period of 10-Mar-2014 and 14-Mar-2014. The electricity and reserve prices on the NEMS during this time period are shown in Fig. 3.

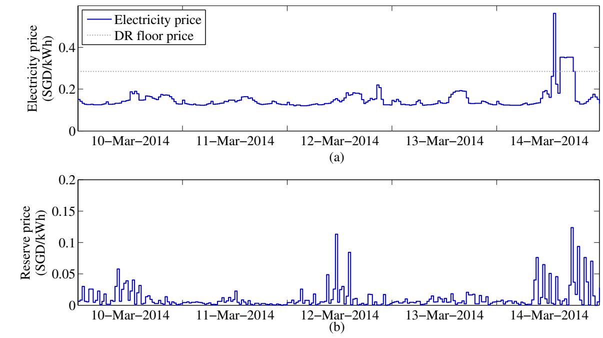

Fig. 3. Electricity and Reserve Prices

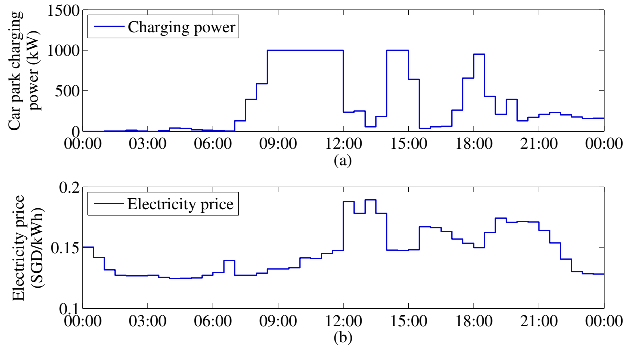

Fig. 4. Car park charging power and electricity price

A. Case 1: Base Case

For the base scenarios no incentives are considered. The optimisation is run and the least cost solution for charging the EVs considering the electricity price is obtained. Fig. 4 shows the simulation results for 10-Mar-2014. The solid lines in Fig. 4 (a) and (b) show the charging power for the car park and the electricity price during that period respectively. The total charging cost for the car park is minimized by charging during low price periods, e.g., from 9:00 to 12:00. Charging during periods from 12:00 to 14:00 is avoided due to the higher electricity costs. In order to satisfy the EV SOC requirements, charging during relatively high-priced periods is still required, e.g., from 18:00 to 21:00.

B. Case 2: Participation in the IL Programme

For this scenario, the total cost is minimized by simultaneously optimising the charging power and the reserve capacity . The results for 10-Mar-2014 are shown in Fig. 5. The solid filled area shows the total charging power for the car park and the striped region depicts the charging power that could be curtailed and re-scheduled for future charging. This variable charge is bid into the reserve market and the car park operator receives payments based on the reserve price. The electricity and reserve prices are shown in Fig. 5 (b).

Electric vehicles are preferably charged during low-priced periods, e.g., from 9:00 to 12:00. For EVs that bid their

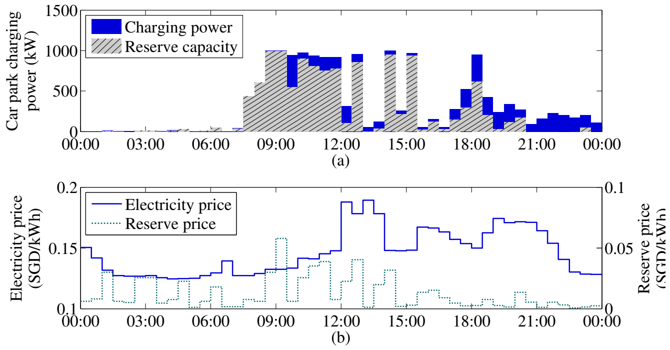

Fig. 5. Car park charging power, variable capacity, electricity and reserve prices

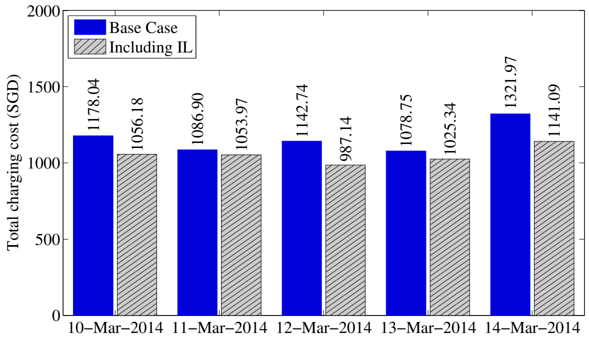

Fig. 6. Comparison of total charging cost for Case 1 and 2

Table III
RESERVE CAPACITIES BID INTO THE DR PROGRAMME FOR 14-MAR-2014

Period	Time	Load Curtailment Capacity (kWh)
30	14:30 - 15:00	17.93
31	15:00 - 15:30	31.99
32	15:30 - 16:00	52.50
33	16:00 - 16:30	8.34

charging loads as IL, the reserve payment is used to offset the cost for electricity. It can be seen that even for the high-priced period between 12:30 and 13:00, the charging power is increased compared to the base case in Fig. 4. This is due to the high reserve prices during this market period.

Fig. 6 shows the optimised total charging cost for Case 1 and Case 2. The total cost of charging is reduced for all the simulated scenarios when participation in the IL programme is considered. Larger reductions in the total charging cost are observed for days with relatively higher reserve prices, e.g., a 13.62% drop on 12-Mar-2014 and a 13.68% decrease on 14-Mar-2014.

C. Case 3: Participation in the IL and DR Programme

Load bids on the DR programme are only scheduled by the MCE during time periods when the electricity price is higher than the DR floor price. Considering the simulation time

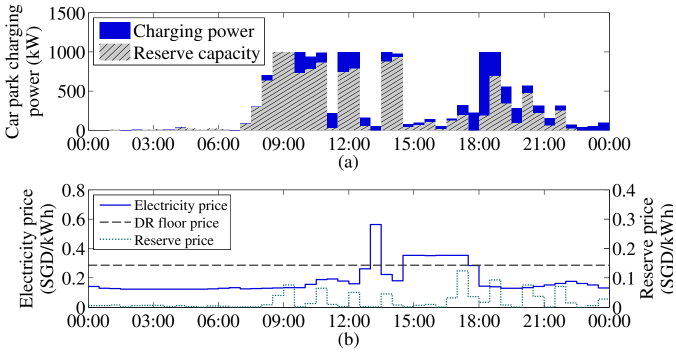

Fig. 7. Charging power and reserve capacity for 14-Mar-2014

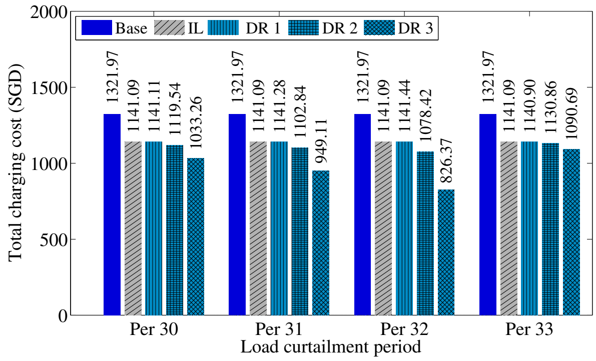

Fig. 8. Total charging cost for 14-Mar-2014 considering IL and DR

period, this condition is only met during a few market periods within 14-Mar-2014. Participation in the DR programme in four of these high-priced market periods is evaluated. Measuring effects of load curtailments on the electricity price is out of the scope of this paper. Three scenarios are used to evaluate different effects on the electricity price. For scenario *"DR1"*, the electricity price is assumed to remain constant. Reductions of 0.001 SGD/kWh and 0.005 SGD/kWh on the $USEP$ are assumed for scenarios *"DR2"* and *"DR3"* respectively.

Changes on the total charging cost for load curtailed during four single periods (Period 30 to 33 on 14-Mar-2014) is studied. The reserve capacity in Fig. 7 is bid as DR and the curtailed load is re-scheduled based on the results obtained by the optimisation problem. Fig. 8 show the results when the bids shown in Table III are scheduled for curtailment. The revenue obtained from the DR programme is directly related to the curtailment capacity and the effect of this on the $USEP$. If loads are scheduled for curtailment, assuming electricity price reductions according to the proposed scenarios, the car park operator will be able to receive very high incentives and reduce the total cost for charging. For instance, assuming the load is scheduled for curtailment at period 32 results in a 0.005 SGD/kWh drop in the $USEP$ price, additional savings up to 23.8% could be obtained if the load is bid into the DR programme instead of the IL programme.

V. Conclusions

This paper proposed a model for arrivals and departures for EVs in a Singaporean car park. Possible revenues obtained by car park operators for participation in the wholesale electricity and reserve market were studied. The objective was to minimize the total charging cost for the car park using a linear programming optimisation problem, the car park model output and real data for a typical week in the NEMS. Simulation results show that participation in the DR and IL programmes may result in additional revenues for the car park operators.

A detailed market model is necessary to study the effects of the load curtailments on the electricity price. Validation of the car park model, aggregation of multiple car parks within the same geographical area and developing a market model are considered areas of key importance for future research.

Acknowledgements

This work was financially supported by the Singapore National Research Foundation under its Campus for Research Excellence And Technological Enterprise (CREATE) programme.

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