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Performance Study of Battery-Powered Electric Vehicles in Macau

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Abstract

With the growing concerns on price fluctuation, depletion of petroleum resources and global warming, environmental and health issues, there is fast growing interest in electric vehicles (EVs) in Macau. Being a city with small geographical size (29.5km^2) limiting the travel range of vehicles, Macau has great potential for EV implementation. There is also a pressing need for researchers and power utilities to develop various infrastructures for EVs and strategies for adapting EVs.

In November 2010, the Macau Government announced to promote “green vehicles” by offering tax incentives in acquisition of “energy efficient vehicles”. During past two years, several public test rides and demonstrations of electric bikes, scooters, mini/mid-size sedans and buses were conducted by manufacturers from Europe, Japan, Taiwan and China.

Three battery-powered EVs (BEVs) were imported to Macau, one by the power company and the other by a car renting company in April 2010 and had been running in real-world for nearly two years; the third was bought by Macau Government in September 2011.

A project was launched to investigate the performance of EV, specifically for sub-tropical environment of Macau. Due to the high temperature and humidity, performance of EVs operated in Macau was yet to be understood. Previous experimental studies conducted in the US, Europe or Japan might not reflect the actual local real-road driving conditions. A BEV was used for experiments and evaluation, while an internal combustion engine (ICE) powered counterpart was used as baseline. This project aimed at the road testing of EVs and evaluation of fuel costs and CO_2 reductions when EVs are adopted in Macau area.

Keywords: electric vehicle, emissions, vehicle performance

1 Introduction

EVs are clean due to their zero local emissions and low global emissions. They are also green due to their environmental friendliness, since electricity can be generated by renewable sources. Despite these obvious benefits, EVs have not been widely used around the world; the key reasons are due to their high price, short driving range or lack of charging facilities.

With an urbanized city and limited land space, Macau has been faced with problems of road congestion and rapid growth in car population. Air pollution is also another important concern. EVs provide low emission urban transportation, even taking into account the emissions from power plants needed to fuel the vehicles, the use of EVs can reduce carbon dioxide (CO_2) emissions significantly. From the energy aspect, EVs are efficient and environmentally friendly [1-2]. Thus, EVs are promising green vehicles that can reduce both energy consumptions and CO_2 emissions [3].

2 Performance studies of BEV in Macau

The Macau Government approved in February 2012 to promote “green vehicles” by offering 50% tax reduction (with a limit of MOP60,000; 1USD ≈ MOP8) in acquisition of energy efficient vehicles [4]. Being a city with small geographical size limiting the travel range of vehicles, Macau has great potential for EV implementation.

The EV study was a collaboration work between the University of Macau (UM) and a local electric power company, Companhia de Electricidade de Macau (CEM), aimed to understand issues relating to EV adoption.

The first project was to evaluate the real road driving performance of EV, specifically for sub-tropical environment of Macau. Due to the high humidity and sub-tropical climate, performance of EVs operated in Macau was yet to be understood. Previous experimental studies conducted in the US, Europe or Japan might not reflect the actual local driving conditions. A Mitsubishi “i-MiEV” was used for experiments and evaluation, while an ICE gasoline-powered version “i”, as shown in Fig. 1 was used as a benchmark.

To support the commercialization and publicity of EVs, an EV charging infrastructure is the underlying foundation, which includes the basic facilities and services to support the operation of a large number of EVs. The second project of this study was to design and implement an EV charging station incorporated with EV management information systems.

3 BEVs for evaluation

The sample EV was imported by the CEM from Japan and subsequently loaned to UM for performance study; while the gasoline-powered vehicle “i” was loaned from the local dealer for comparison.

Figure 1: Vehicles being tested (left: “i-MiEV; right: “i”)

In terms of technical specifications, the “i-MiEV” has a top speed of 130km/h and a range of 160km per full charge (Japan 10-15 mode). Batteries used in the vehicle were lithium-ion batteries with a capacity of 16kWh at 330V. The vehicle takes 6-7 hours for a full charge at a 230V household supply.

The maximum speed of the EV motor is 8,500rpm, and the maximum output is 47kW (3,000-6,000rpm) which is the same as “i” with a turbo ICE. This motor has the specific characteristic of generating high torque from low speed, with the maximum torque is 180 Nm. The compact and lightweight motor was developed to outperform the turbo engine.

The curb weight of the EV is 1,080kg, which is 180kg heavier than the gasoline version, with a 25kW rated permanent magnet synchronous motor (47kW peak). Like most EVs, the “i-MiEV” has regenerative braking capability. Except for the powertrain, which includes the battery, controller and motor, most parts of the system are same as

Table 1 Key properties of the sample EV

Motor type	PM synchronous
Rated power	25kW
Maximum power (net)	47kW
Maximum torque (net)	180N•m
Battery type	Lithium-ion
Battery voltage/capacity	330V/16kWh
Charging time	~7 hours (230V)/ ~30 minutes (Quick charged to 80% at 3-phase 200V/50kW)
Single-charge range	160km
Curb weight	1,080kg

(a)

(b)

(c)

(d)

Figure 2: Other BEVs in Macau: (a) Car renting company; (b) Macau Government; (c) For public trial; (d) UM

the gasoline version. Key properties of the EV were shown in Table 1.

Since the announcement of tax incentives in acquisition of “energy efficient vehicles” in November 2010, various manufacturers from Europe, Japan, Taiwan and China were attracted to demonstrate their EVs in Macau. Several public test rides of electric bikes, scooters, mini/mid-size sedans and buses were conducted during past two years; some of them are shown in Fig. 2. Three BEVs were imported to Macau, one by CEM and the other by a car renting and had been running in real-world for nearly two years; the third was bought by Macau Government recently.

4 Performance evaluation

Several tests were proposed for evaluation of the sample EV: laboratory and road tests. Test configurations were shown in Fig. 3. The EV was proposed to be tested with a programmable chassis dynamometer to simulate different road conditions as shown in Fig. 4. The performance of the EV, such as power, torque, speed and brake specific energy consumption, could be measured and recorded. The proposed configuration for road tests was shown in Fig.

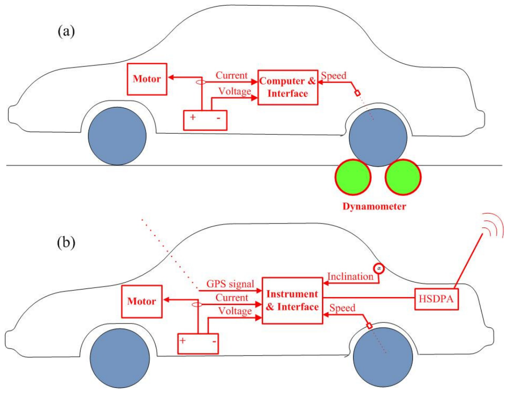

Figure 3: Proposed testing configuration for (a) laboratory tests; (b) road tests.

Figure 4: BEV testing on chassis dynamometer.

3(b), with more information to be captured, GPS position, and inclination data. Since the EV will be testing on the street, HSDPA modem was used for remote data retrieval purposes. The data available through the on-board sensors enable capture of pertinent information for the experimental evaluation of the EV.

4.1 Fuel Consumption and Emission

The concept of real-road driving conditions was emphasized in the test routes rather than collecting data synthesized from simulated conditions using a chassis dynamometer in a laboratory, as it would not have been the real driving conditions. Moreover, aerodynamic resistance during road testing also has a significant effect on reducing the overall driving range.

The road driving test was conducted with both an EV and a gasoline-powered counterpart. Fuel consumption and greenhouse gas emission were evaluated and compared for both vehicles.

Emission data published by the vehicle manufacturer [5] were used to estimate the CO_2 displaced during the test; while the emission data of electricity generation plants were used to estimate the atmospheric emissions for re-charging the EV after the road test.

During the performance evaluation exercise, a primitive approach was adopted for evaluating the fuel consumption. Before the road test, the EV was fully-charged while the gasoline vehicle was fully-fueled. After the road test of ~82km, the electricity consumption to fully-recharge the EV and the gas consumption were recorded. Local electricity and gasoline prices were used for comparison.

4.2 The Test Routes

Test route was devised based on typical driving conditions of business users in Macau: urban, sub-urban and highway with about 40km per lap, as shown in Fig. 5.

Macau and Taipa are connected by three bridges (with only two opened for public users) with a

Figure 5: Test route (≈40km per lap).

speed limit of 80km/h. The test route was designed to cross the river and return to Macau. It utilized the strategic location of CEM office that in close proximity to the city center which include many start-stops during the road test. Macau is relatively flat geographically in most of its area. However, many people were skeptical about the EV performance on steep slopes. Hence, the test route was also designed to test the capability of the EV to climb up some mild slopes. Results from the test drive were just a first step of a more comprehensive research. More road conditions with different test routes and longer drives shall be conducted for different groups of vehicle users in the future.

4.3 Road Test and Result

Both vehicles were tested together for two laps and the sequence of driving was interchanged during the second lap in order to balance the effects of different driving habit of drivers. The test was conducted on 23 April 2010, started at 10:00am and completed around 1pm, with frequent start-stops in downtown area during lunch hours. Summary of primary results were shown in Table 2. Differences in distance travelled were due to location between the gas station and charging station.

Table 2 Primary test results

	i-MiEV	**i** (ICE)
Distance travelled	81.7km	82.4km
Fuel consumption	12kWh (electricity)	5.076 Liter (gasoline)

Table 3 Fuel cost and consumption (1 USD≈MOP 8)

	EV	**ICE**
Fuel price (MOP)	1.223 per kWh	9.85 per Liter
Fuel consumption	0.1469 kWh per km	0.0616 Liter per km
Distance travelled	6.81km per kWh	16.23km per Liter
Fuel cost per distance travelled (MOP)	0.1797 per km (29.6%)	0.6068 per km (100%)

Table 4 Comparison of CO_2 emissions

Electricity generation	**EV**	**ICE**
383.16g/kWh	56.278g/km (48.1%)	117g/km (100%)

Unit fuel costs for the day of road test were listed in Table 3, fuel per unit distance and distance to be travelled per unit fuel were also calculated and tabulated in the same table. From the table, we can see that the fuel cost saving achieved was around 70.4%. Furthermore, the driving range by one full-charge of the 16kWh battery was estimated to be 109km in Macau.

EVs are clean due to their zero local emissions, but the global emissions depend on how electricity is generated. In Macau, natural gas, heavy oil and diesel were used; electricity was also imported from mainland China, where coal was the primary fuel.

In order to compare the CO_2 emissions for both vehicles, atmospheric emissions data of local electricity utility were used to estimate the CO_2 emissions for re-charging an EV. On the other hand, exhaust data published by the vehicle manufacturer [5] were adopted to estimate the emission during the road test. CO_2 emission from power plants needed to re-fuel the EV was tabulated in Table 4, exhaust from the gasoline-powered counterpart was also estimated and included in the same table. From the table, we can see that the CO_2 emission was reduced by 51.9% when EV was adopted.

5 EV Charging Facility

BEVs are one of the solutions proposed to tackle the energy crisis and global warming. However, the high initial cost, short driving range and long charging time have proved the limitation of BEV [1-2]. The market of EVs remains in extremely limited extent by weight, lifetime and the constraint of cruising radius by one charge.

The daily energy consumption by an EV will be determined by the driving range/cycle and the charging time, while its impact on the electricity system demand will depend on the duration and pattern of charging.

The electric utility‘s interest in EV lies in the anticipated and expected benefits beyond the simple increase in energy sales. It is expected that the EV charging load will be contained within system off-peak hours without affecting the peak demand, thus increasing the sale of low cost electricity. From the electric utility operation aspect, this potential to fill the valley [6] in the load curve will result in more electricity sales for the same system capacity [7].

In some countries, it was considered that the EV battery to be one of the energy source when it is not moved. So it is very attractive to extract electricity from the EV battery, especially for private use, that can be seen not to be used around noon. The implementation of such vehicle-to-grid (V2G) technology depends on the communications support, interfaces for communication between the power grid, charging points and EVs [8].

In the second project, an EV charging station had been designed with the EV charging load programmed and shifted to fill the valley of the system load curve without regard to localized effects [7] and the EV charging loads would be contained within system off-peak hours without affecting the peak demand.

This project focused on the development of charging facilities for the possible market of EVs in the Macau area, the proposed charging stations incorporated with the EV management information system, are particularly suitable for both business users and public utility; with some modification to include a payment system when they are installed for general public.

5.1 Design of EV Charging Stations for Macau

The impact of EV loads on the energy demand is determined not only by the number of EV in use and their usage pattern, but also by the number of EV being charged at any instant and the charging profile of the battery module. It would be logical to charge an EV only during the off-peak hours so as to fill up the valley in the system load curve; it may not always be feasible. The following factors were investigated to facilitate the design of the charging station:

- The load curve of electric utility;
- The electricity tariff structure;
- The travel model of vehicle users;
- Typical battery charging curves.

5.2 Electricity Demand Curve and Tariff

A load diagram of CEM is shown in Fig. 6, while the electricity tariff structure is tabulated in Table 5. From Fig. 6, the system load decreases after 20:00 hours until 08:00 hours of the following day. The power company defined the off-peak period from 20:00 hours to 09:00 hours of next

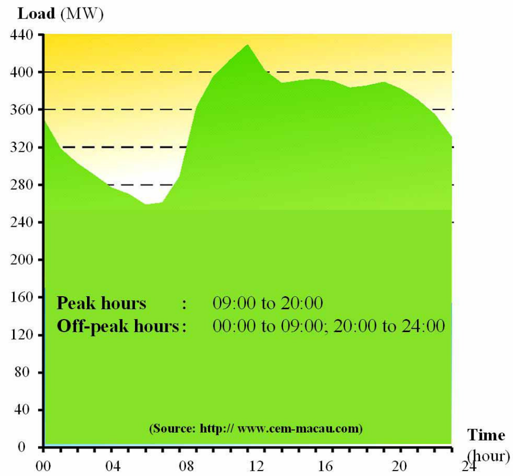

Figure 6: Typical daily load curve.

Table 5 Electricity Charge (MOP)

Demand		21.484 per kW
Active Power	Peak hours	0.874 per kWh
	Off-peak hours	0.767 per kWh
Reactive Power	Peak hours	0.348 per kVARh
	Off-peak hours	0.116 per kVARh

morning as shown, according to the recorded load curves.

From the utility's point of view, the EV battery charging should proceed within the off-peak hours, in order not to increase the system demand and the installed generation, transmission and distribution facilities, and they are sufficient to cater for those additional EV charging loads. As a user, it would also be more economical to charge their EVs during the night-time with a comparatively lower power charges as depicted in Table 5.

5.3 Driving Habit in Macau Area

Motorcycles are not only widely used by private users but also business users. More than half (53.9%) of licensed vehicles in Macau are motorcycles (111,198 recorded at the end of 2011). It is straightforward to broaden the EV market by first choosing electric-bikes (E-bikes).

The travel patterns of different types of motorcycle user were schematically shown in Figs. 7 to 8, and night-charge periods were imposed on the same diagram when an E-bike is employed. In Fig. 7, charging would happen at any instant if not properly organized. Furthermore, V2G was not suitable for Macau since most private vehicle users would travel during lunch hours. The average

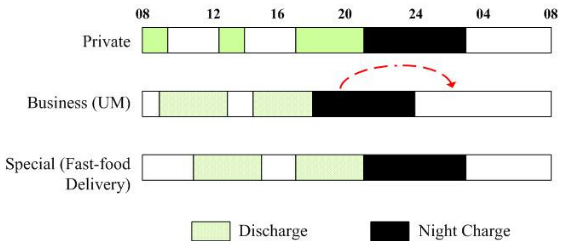

Figure 7: Travel model of different types of vehicles

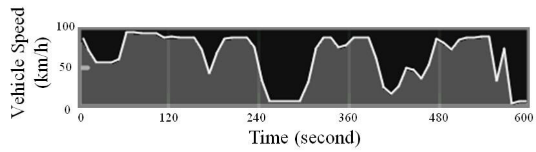

Figure 8**:** Typical driving pattern in Macau

Table 6 Typical Cruising Ranges

Private	8km
Business (University)	20km
Special (e.g. Fast-food delivery)	40km

Table 7 Properties of the sample E-Bike

Vehicle type	Scooter
Motor type	Brushless a.c.
Rated power	0.6kW
Maximum power	1.2kW
Battery type	Lithium- ion
Battery voltage/capacity	25V/14Ah
Charging time	~4 hours (90%)/ ~6 hours (100%)
Range (Fully charged)	45km

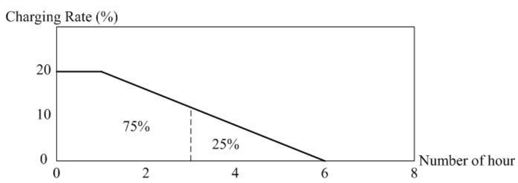

Figure 9**:** Battery charging characteristic of the sample E-bike (6-hr charge)

cruising range of different users in Macau area was also summarized in Table 6.

If no additional measures to manage the charging loads, the EV charging loads would create an additional burden to the power system components. The major purpose of this project is to delay the EV charging loads to after 20:00 hours and contain them within the off-peak period defined by the power company.

5.4 Electricity Demand by Night-charge

The characteristics of a typical E-bike being studied were tabulated in Table 7, with a battery charging rate (temporal variation of the charging load per unit of recharging energy) shown in Fig. 9. As shown in Table 7, the maximum range per one night-charge was 45km, which was greater than the average cruising range of most users in Macau, so one night-charge was sufficient to fully recharge an E-bikes for all general users. As shown in Fig. 9, the time for a full charge is about 6 hours.

5.5 Shifting of Charging Loads

In Fig. 6, the off-peak period defined by the power utility was between 20:00 hours in the evening to 09:00 hours in the next morning, the total duration of off-peak period was thirteen hours. From the sample charging current shown in Fig. 9, 75% of the battery would be charged within three hours. It is proposed to divide the EV loads into different groups, and the start-time between groups would be separated by two to three hours. The anticipated charging currents were simulated with different combinations of group/separating hour. Simulated results were shown in Fig. 10.

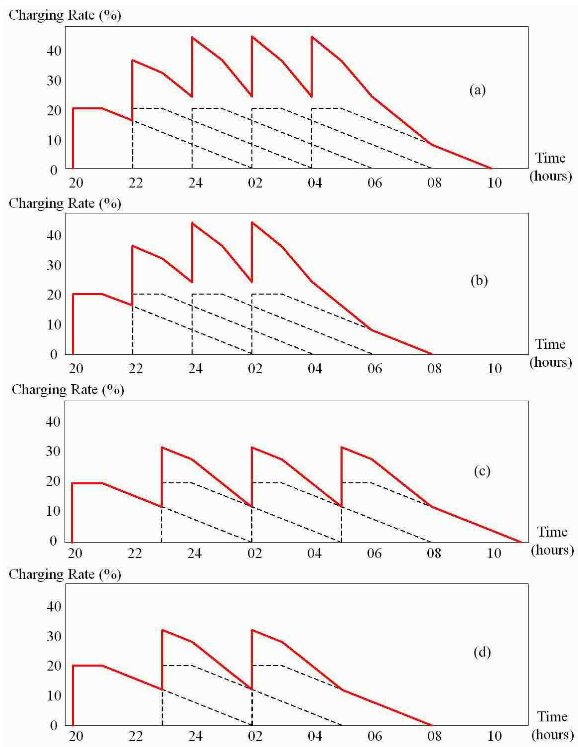

Figure 10: Simulated charging characteristics for different combination of groups/separating hours: (a) 5/2; (b) 4/2; (c) 4/3; and (d) 3/3

5.6 Design of EV Charging Station

The charging station for UM was primarily intended to demonstrate the practical implementation of theoretical approaches mentioned in previous sections and to be served as a teaching tool for academic programs. The overall structure was shown in Fig. 11.

The charging station was a system for connecting EVs to the power grid for refueling (charging). The hardware and software concept covered user authentication, management, measurement and fleet administration.

The whole system were implemented with an industrial PC, proximity card reader was used for validating and recording activities of both drivers and vehicles. When checking-out an EV, drivers were required to use their staff card for validation with PIN. Both staff card and vehicle card were required for checking-in an EV, car-park number and odometer readings were also required. Numeric keys on the touch-screen have been integrated as an input/output interface for drivers and facilitate intuitive operation of the charging station. An intelligent energy meter was installed to monitor the electric power consumption and other relevant electrical parameters such as power quality performances; the control features of the energy meter were also used for initiating delayed charging at pre-programmed time intervals.

In Fig. 11, the charging station was designed to fuel a fleet of nine E-bikes, with their charging start-time divided into three groups, with starting times at 20:00, 23:00 and 02:00 hours respectively, according to scenario (d) in Fig. 10. When more EVs were to be adopted, the charging loads (divided to four groups and separated by two hours) as shown in Fig. 10(b) would still be absorbed within the valley of the demand curve, without additional burden on the maximum demand.

Since not all EVs were fully discharged when returned, the system was also designed to record the odometer readings and an intelligent energy meter was installed to record their respective charging profiles. Data collected would be utilized to determine the grouping combinations for delayed charging in the future. If the travel distance of any EV returned (during lunch break for example) was greater than the 70% of its maximum cruising range, the charging station was programmed to start charging immediately. Proximity cards and reader were for administration and identification purposes, and could be replaced by a payment system when the charging station was installed for general public. Moreover, electrical safety, charging, measurement and protection systems were designed according to current international standards. A simplified prototype with only one socket outlet was built for experimental verification as shown in Fig. 12.

6 Conclusion

EVs are clean due to their zero local emissions and low global emissions. They are also green due to their environmental friendliness, since electricity can be generated by renewable energy sources to achieve sustainable mobility and zero emissions

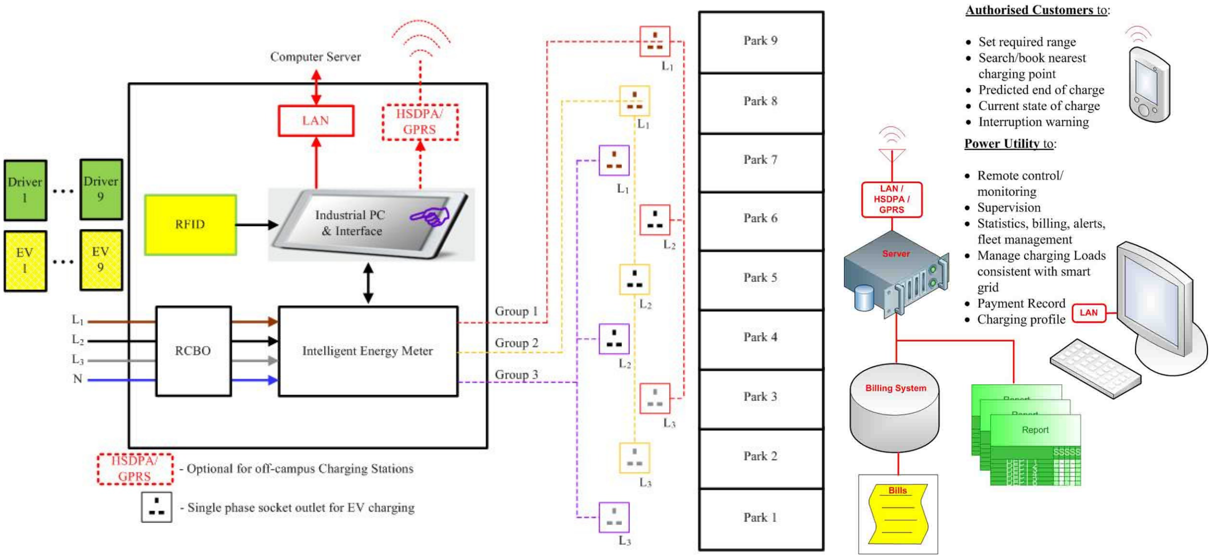

Figure 11: Schematic of the EV charging station, computer server, billing & reporting systems

Figure 12: Experimental prototype.

[9].

With the growing concerns on oil price fluctuation, depletion of petroleum resources and global warming, there is fast growing interest in EVs in Macau. Before adapting EVs in Macau, a battery-powered mini EV was recently tested with real driving conditions in sub-tropical environment of Macau. Results revealed the driving range by one full-charge was about 109km, a fuel cost savings of more than 70.4%, and CO_2 emission was significantly reduced by 51.9%. Additional reduction could be achieved when more renewable energy sources or non-coal electricity was used for the generation of electricity.

Results from the road testing were just a first step of a more comprehensive research. More road conditions with different test routes and longer drives shall be conducted for different groups of vehicle users in the future.

On the other hand, an EV charging station was designed and implemented for connecting EVs to the electric power grid for charging. The proposed systems not only provided the fleet administration and load management features, but also shift/delay the battery charging period within the utility's defined off-peak period, conveniently filled the valley in the system load curve without regard to localized effects.

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