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Electric-drive vehicles for peak power in Japan

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Abstract

Electric-drive vehicles (EDVs), whether based on batteries, engine-electric hybrid, or fuel cells, could make major contributions to the electric utility supply system. Computer-controlled power connections from parked EDVs would provide grid power from on-board storage or generators. Kempton and Letendre conclude that, in the United States, battery EDVs can be cost-effective as a source of peak power (Kempton and Letendre, 1997) or as spinning reserves (1999). This option is even better matched to urban Japan, where vehicles are typically parked throughout peak electrical demand periods. Using Ministry of International Trade and Industry (MITI) forecasts for the number of zero emission vehicles in 2010, we estimate the maximum potential power from EDVs in the Kanto region (which includes Tokyo) at 15.5 GW, 25% of Kanto's 1998 peak demand. This paper calculates the cost to provide power from five current EDVs — both battery and hybrid vehicles — and compares those costs to current purchase rates for independent power producers (IPPs) in Japan. Battery characteristics are calculated from current manufacturer-provided data as well as the California Air Resources Board (CARB) projections. Given current vehicle battery costs and current utility purchase rates, no vehicles would be cost-effective peak power resources. Given CARB projections for batteries, the Nissan Altra is cost-effective as a utility power source. Using projected IPP purchase rates for peak power and CARB battery projections, the Nissan Altra and Toyota RAV4L EV are cost-effective. The net present value to the electric grid could be near 300,000 yen ($US 2500) per vehicle. If utilities take advantage of this opportunity to purchase peak power from vehicles, it would make the electric grid more efficient, enlarge the market for EDVs, lower urban air pollution, and facilitate future introduction of renewable energy.

Keywords: Electric vehicles; Hybrid vehicles; Peak power; Energy storage

1. Introduction

Electric-drive vehicles (EDVs) have gained attention in the past few years due to growing public concerns about urban air pollution and other environmental and resource problems. In the United States, the California Air Resource Board (CARB) instituted an ambitious requirement for 10% of the new cars sold in the state to be zero-emission vehicles (ZEVs) by the year 2003, versions of which have been adopted by other states (Nadis and Mackenzie, 1993, p. 72). This boosted the development of EDVs and accordingly many auto-manufacturers have developed their own EDV models to meet this goal. EDVs include three primary types: battery-based, hybrid, and fuel cell. Battery and fuel cell vehicles are considered ZEVs, while hybrids are low-emission or ultra-low emission vehicles.

While an increase in battery-based EDVs is expected to increase electricity sales, extra generation capacity is not needed if the EDVs are recharged at times of low demand, such as overnight. In fact, as we argue here, there is a potential to *reduce* the peak load if EDVs are grid-connected to allow discharging of the electricity stored in their batteries, or running their on-board generators, during times of peak demand. This approach was suggested by Kempton and Letendre (1997,1999), who calculated the economic value of discharging battery electric vehicles as a peak power source and as spinning reserves. Kempton and Letendre conclude that in the US, under the right conditions, it can be cost-effective for the utility as well as for the vehicle owner. That is, the value to the utility of tapping stored electricity is greater than

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the total costs to the vehicle owner: two-way electrical connections, purchased energy, losses in charging and discharging, and the cost of wear from additional cycles on the battery. Kempton and Letendre (1997) also outline the design of a controller which would allow the utility to tap power when needed, limited by constraints set by the driver (for example, "I must have enough charge by 7 a.m. tomorrow to drive 20 km").

In Japan, energy security issues are even more serious than in the US mainly due to its scarce resources. Japan has one of the lowest energy intensities (energy-use per unit of GNP) in the industrialized world, but its aggregate energy-use is still rising. While the government seeks nuclear power to solve both energy scarcity and greenhouse gas mitigation, the national debate on nuclear energy has been rapidly intensifying. The government is also engaged in several renewable energy programs, such as rooftop solar photovoltaic (PV) generation. Storage in EDVs improves the economics and performance of both nuclear and solar: Nuclear is best run at constant output, so storage helps even out the peaks and troughs of demand, while renewable energy fluctuates with sunlight or wind, so storage helps even out supply. Storage also helps solar match supply to demand peak, since the solar peak is a couple of hours earlier than the typical load peak. Therefore, EDVs would seem to be a promising way to add storage to the electric system, especially for a country like Japan, since automobiles are not used as frequently as in other industrialized countries, and since urban automobiles are typically idle through and past peak hours. Consequently, there are more vehicles available to be discharged during peaks, and each one can allow deeper discharge.

This paper applies the methods of Kempton and Letendre (1997) to evaluate the economic potential of EDVs for the Kanto region of Japan. The Kanto region houses major cities such as Tokyo, Yokohama, and Chiba. Although not analyzed here, we believe that EDVs can also be useful as peak power sources in the Kansai region (including the cities of Osaka, Kobe, and Kyoto), Chubu region (including Nagoya), and parts of other regions that have major cities with comprehensive public transportation systems as well.

The utility serving the Kanto region, the Tokyo Electric Power Company (TEPCO), has faced significant challenge in meeting its peak demand every year.[1] In fact, TEPCO's annual load factor is low, below 60% (TEPCO, 1999, p. 29), mainly due to the enormous demand for space conditioning during the summer and winter. The policies we suggest would tap EDVs to reduce peak generation need, and thus reduce the need for further investment in peak generation capacity.

[1] Peak demand was a problem until the recent depression of the Japanese economy. This reprieve is seen as temporary, as TEPCO forecasts its peak electricity demand in 2007 to rise by nearly 20% from 1998 (TEPCO, 1999).

Table 1
Service region of TEPCO compared to national totals[c]

Prefecture	Population (million)	Elec. sales (billion kWh)	Number of automobiles (million)[a]
Japan total	124.3	785.3	72.2
TEPCO[b]	42.3 (34.1%)	265.4 (33.8%)	22.0 (30.5%)

[a] Includes light vehicles but not motorcycles.
[b] Numbers in parentheses indicate ratio to national total.
[c] Source: TEPCO (1999), MITI (1999).

2. Market potential

2.1. TEPCO service region

The service region of TEPCO covers the eight prefectures of the Kanto region and the eastern half of Shizuoka prefecture, with a total population of 42 million (about one-third of the country). Its annual electricity sales for 1998 was 265 billion kWh (TEPCO, 1999). Table 1 shows the population, electricity sales, and the number of automobiles in the TEPCO service region compared to Japan overall.

2.2. Potential maximum power output

We begin our analysis with a simple calculation of the potential peak resource from electric vehicles. According to MITI's Natural Resources and Energy Agency (NREA), the target of "clean energy vehicle" ownership in the year 2010 is 3.4 million vehicles (Ishizuka, 1998). "clean energy vehicle" includes EDV, natural gas, and methanol fueled vehicles. Assuming that half of the clean vehicles will be EDVs, and that 30.5% of vehicles are in the TEPCO service region (see Table 1), we project the number of EDVs in 2010 in the TEPCO service territory to be 518,000. Using a maximum output power between currently sold battery and hybrid EDV models of 30 kW (see Table 2), the estimated total potential for TEPCO is 15.5 million kW (15.5 GW) of EDV power capacity, approximately 25% of the 1998 peak demand (59.2 GW on July 3; TEPCO, 1999). Due to infrastructural limits on residential house wiring, the near-term potential for vehicles in home garages is approximately 10 kW per vehicle, thus if all vehicles were tapped at home, the total would be 5.2 GW. For comparison, a large nuclear power plant produces about 1 GW. A source of peak power

Table 2
Characteristics of selected EDV configurations and their storage systems (modified from Kempton and Letendre, 1999)

Electric-drive vehicle (EDV) model	Total energy storage (kWh)[a]	Depth of discharge (%)	Peak output (kW)	Efficiency (km/kWh)	Vehicle range (km)	Cost of storage system ($/kWh)	Storage system cycles
GM EV1, sports car (Pb/acid)	16.80	85%	100[b]	8.96	128	150	300
Toyota RAV4L EV, sport utility vehicle (NiMH)	27.36	75%	45	10.48[c]	215	300	1000
Nissan Altra, passenger car (lithium ion)	34.56	95%	55	6.09[c]	200	300	1200
Nissan Altra, passenger car, assuming CARB projections (lithium ion)	34.56	95%	55	10.00	328	200	2200
Toyota Prius (parallel hybrid), meeting California 20-mile requirement (NiMH)[d]	5.50	60%	21	(see below)	(Fueled vehicle)	444[e]	1700[f]

[a] Capacity of battery, neglecting the 5–10% loss through the on-board inverter (for the entire charge-discharge cycle, these losses occur twice, plus some losses in battery acceptance of charge). Losses are included in our subsequent calculations.
[b] Short-term peak output for acceleration, not sustainable.
[c] Efficiency was calculated from Toyota and Nissan's claimed electrical capacity and claimed range.
[d] Assumes 10 km/kWh, with battery sized up to accommodate 20-mile range (33km), while only allowing 50% depth of discharge.
[e] Using forecasted future manufacturing cost of $800/1.8 kWh unit (Duleep, 1998).
[f] Data from Panasonic giving 1500–1900 cycles for 60% depth of discharge.

between 5.2 and 15.5 GW would be a very significant resource for TEPCO.

2.3. *Cultural aspects of vehicle use in Japan*

In the urban areas of Japan, vehicles are not typically used as frequently as in the US. Especially in the Kanto region, the majority of vehicle owners use public transportation (train and bus) exclusively to commute to their office, and only use their private vehicles on weekends for recreational purposes. Shopping is usually done daily at the numerous small stores around the closest train station to home. Since significant electrical peak demands in Tokyo occur only on weekdays and not on weekends, this cultural aspect makes an excellent match of EDVs to serve as a peak power source in Japan, better than in the US. The analysis in Kempton and Letendre (1997) uses data from Kurani *et al.* (1994) on the average "range buffer" which US drivers perceive to be needed for emergency purposes or an unexpected trip to the store — 32 km for most US drivers. In the urban areas of Japan, people use public transport or an ambulance to get to the hospital and would walk to the store for an unanticipated need. This would allow a smaller "range buffer", which would lead to higher output or longer period of peak reduction.

3. Vehicles analyzed

The economic potential of EDV grid storage varies by the battery type, cost, maximum voltage, and vehicle characteristics. Thus we will use the five vehicles described below, and summarized in Table 2, for our analysis.

The first example vehicle is the GM's EV1, which uses a lead–acid (Pb/acid) battery. Among battery types, Pb/acid has the disadvantages of short cycle life, high weight, damage from deep discharge, and environmental lead pollution during manufacturing and recycling (Lave *et al.,* 1995; Allen *et al.,* 1995). On the other hand, this is the most mature battery technology and has a low initial cost.

The second vehicle we analyze is the "Toyota RAV4L EV", which uses nickel metal hydride (NiMH) batteries. We assume the cycle lifetime claimed by Toyota of 1000 battery cycles. These batteries are being manufactured by Panasonic (1996), which is currently in very limited production. The Toyota vehicle is leased, not yet sold, in Japan so end-use customers never buy batteries. For production NiMH battery pricing, we draw on the most detailed cost study of which we are aware (Lipman, 1999), which projects NiMH battery costs based on production of 20,000 units/yr in 2 yr, assuming no technical advances and assuming manufacturer but not retail markups ("OEM prices"). Lipman's resulting NiMH battery cost figure is $266–$287 $/kWh. We use $300/kWh (36,000 yen/kWh) in our calculations.[2]

The third example is a Nissan vehicle based on lithium-ion batteries made by Sony. This vehicle is being marketed in the US under the name Altra (in Japan it is currently being leased under the name "Renessa"). Among analysts in mid-1999, the lithium-ion battery seems to be considered the most promising of current technologies as a vehicle battery. We have less firm data on costs for this battery; again no current cost data are provided by the manufacturer (Sony) and they are not in mass production. The CARB's Battery Technical Advisory Panel has estimated that when production reaches 20,000 units, vehicle lithium-ion batteries would cost $150/kWh and have a life of 2200 cycles. For our third example vehicle, we make conservative interpretations of these projections, giving double this projected cost of lithium-ion batteries and use the manufacturer's current cycle life projection (1200 cycles) as characteristics of the Nissan vehicle. We also use the manufacturer's claimed range of "200+ km", which we feel is understated, as that would imply an unrealistically low 6 km/kWh efficiency.

As a fourth example, we use the Nissan lithium-ion vehicle with CARB's projected cycle life. We also assume a more realistic 10 km/kWh efficiency, which at 95% discharge permitted for lithium-ion would imply a range of 328 km. Nevertheless, even in this case we inflate CARB's cost projection to $200/kWh. The reader who wishes to stay closer to announced performance characteristics could ignore our Altra-CARB example, as it is based on projections of both battery cost and cycle life. However, we feel we would present a misleading picture if we based our entire analysis on current performance and near-term costs, as these are emerging technologies for which major corporations have made substantial commitment for continuing development.

Finally as our fifth example, we use Toyota's Prius, a parallel hybrid vehicle, which uses both an internal combustion engine and an electric motor for drive power. (The parallel hybrid uses both engine and electric motor to drive the wheels, as contrasted with the series hybrid, whose combustion engine drives a generator, and the wheels are driven exclusively by electric motors.) Hybrid vehicles generally have smaller batteries than battery EDVs. The current configuration of the Prius has only 1.8 kWh storage capacity, which is not enough to be interesting as a source of utility power. Some hybrid vehicles may have larger batteries, to meet the proposed California requirement of a 20 mile battery-only range (this would allow most hybrid vehicle trips in the US to be in a battery "ZEV mode"). Using Panasonic's forecasted battery cost of $444/kWh and the current 1.8 kWh storage, the Prius was not cost-effective for grid power. To make this a more interesting comparison, in our analysis we will assume a Prius with a scaled up battery of 6.6 kWh (to go 20 miles, assuming a 10 km/kWh efficiency). As we shall see, this assumed larger battery does not affect our conclusions. Much more power could be provided from a hybrid like the Prius if the motor generator, rather than just the battery, were used to provide grid power. However, we do not analyze this possibility.[3,4]

4. Conditions for analysis

This analysis adopts the general approach of Kempton and Letendre (1997) but differs in several characteristics. Kempton and Letendre calculated peak power value in the US based on avoided cost, whereas we calculate value in the TEPCO region from announced rates and from rates extended to account for the economics of infrequent use. These rate schedule differences lead to a simpler (and more realistic) calculation of cost-effectiveness, as we shall see. This analysis also is based entirely on announced vehicles, whereas the Kempton and Letendre analysis had to draw more on prototypes. Losses in charging and discharging are explicitly included in the present analysis; they were mentioned but not calculated by Kempton and Letendre (their effect is small). As mentioned earlier, the timing of automobile use is more favorable in Japan with respect to peak load, so some assumptions are more favorable to the analysis in Tokyo than in the US. The only other similar published analysis we know of is Kissock (1998) for fuel cell vehicles, but Kissock assumes that the fuel cell runs when parked, whereas we assume only battery power is tapped, even for the hybrids. Kissock also takes no account of the premium value of electricity at peak hours, which we feel is critical to the analysis.

4.1. Rate structure

The electric rate structure in Japan is quite different from that in US. In Japan, all contracts, whether residential, commercial, or industrial, consist of a base-load

[2] We convert at 120 yen/$US, the exchange rate in early 1999.

[3] To use the hybrid motor generator for grid power when the vehicle is parked, a thorough safety analysis would be needed for the exhaust gasses. This is even an issue for fuel cell vehicles, because the CO_2 exhaust, while "nonpolluting" and nontoxic, could cause suffocation in an enclosed garage. Such problems may well be solvable with redundant safety mechanisms. Nevertheless, to keep our analysis simple, we assume that hybrid vehicles provide power only from their battery, not the motor-generator.

[4] Personal communication, Timothy Lipman, University of California, Davis, May 1999.

Table 3
Rate structure of TEPCO: Regular contract and variable time zone contract[b]

	Regular contract (C)[a]		Variable time zone contract		
		Rate (yen)			Rate (yen)
Base load charge	Constant rate	260/kW/month	Contract ⩽ 6 kW		1200/month
			Contract > 6 kW	Up to 10 kW	2000/month
				Excess 10 kW	260/kW/month
Energy use charge	Up to 120 kWh	16.85/kWh	Daytime (7 a.m.–11 p.m.)	Up to 90 kWh	22.05/kWh
	120–280 kWh	22.40/kWh		90–210 kWh	29.30/kWh
				210 kWh above	32.25/kWh
	280 kWh above	24.65/kWh	Nighttime (11 p.m.–7 a.m.)	Constant rate	6.15/kWh

[a]Regular contract B (not shown in table) is the most common among current residential households without EDV ownership, but to secure capacity for quick charging, an additional 6 kW is preferable under contract C since the maximum base-load contract for contract B is 6 kW for the entire house. The rates for the two contracts are very similar.
[b]Source: TEPCO (1999).

charge and an energy-use charge. The energy-use charge is the same as in the US and depends on the energy, in kWh, used. The base-load charge depends on the maximum peak, in kW, that the household or facility is permitted to use. They can not receive more kW than the contract limit; it is limited by a circuit breaker. The following analysis is based on residential contracts.

In Japan, the government regulates utilities to purchase "reverse flow" electricity from consumers (i.e. electricity generated via rooftop solar systems) at the rate which the utility sells electricity to the consumer. For EDVs, a more appropriate regulation is desired since battery EDVs will be charged during off-peak periods when the generation cost is at its lowest, and discharged during peak periods when the generation cost is highest. TEPCO offers different contracts to consumers, and the most suitable contract for EDV owners will be considered here for economic analysis.

To maximize the benefit to the utility from battery-EDV storage, it is best to charge the batteries at night and discharge them during the peak time in the day. Hybrid EDVs would discharge during peak times, but could recharge from their on-board generator during driving. TEPCO offers a "variable time zone" contract that sets the daytime (7 a.m.–11 p.m.) rates approximately 30% higher and the nighttime (11 p.m.–7 a.m.) rates approximately 70% cheaper than the regular contract. Table 3 shows the rate structure of the two different contracts. The variable time zone contract is the most suitable contract for EDV owners, since it does not restrict the EDV to be charged only during nighttime (inconvenient in emergencies) like the other peak-shift-oriented contracts does.

Table 4
Household electricity contract and consumption (data from TEPCO, 1999: Kempton and Letendre, 1997: Toyota, 1999)

Year	Household consumption (kWh)	Including EDV energy requirement of 83.3 kWh[a] (kWh)	Contract capacityf (kW)	Including EDV required capacity of 6.0 kW[b] (kW)
1995	286.7	370	2.991	8.991
1996	280.4	363.7	3.058	9.058
1997	284.3	367.6	3.115	9.115

[a]Assuming an annual driving distance of 10,000 km and EDV efficiency of 10 km/kWh, from Table 2.
[b]Capacity needed to use Toyota RAV4 EV's charging unit. The GM EV1 requires 1.2 kW for 15-h charging and 6.6 kW for 3-h charging.

In Table 3 we can see that the rate for nighttime electricity for the variable time zone contract is as low as 6.15 yen/kWh. The daytime rate is as high as 32.25 yen/kWh, indicating the higher value of daytime electricity and in turn the potential value of grid-connected electricity storage.

The average load for households in 1995–1997 are shown in Table 4. The second and fourth columns are the actual average household electricity consumption and contract capacity during 1995–1997, respectively, and the third and fifth columns are the estimated consumption and contract capacity with EDV ownership, respectively. We use these numbers as an example in our following economic analysis.

Using data from Tables 3 and 4, the economic benefit for battery EDV owners is calculated in Table 5. It is

Table 5
Result of savings by switching contracts, using 1997 TEPCO data

Input data			Monthly charge		Savings	
Contract	Household use	EDV use	Regular[a]	Day/night[b]	Monthly	Annual
(kW)	(kWh)	(kWh)	(yen)	(yen)	(yen)	(yen)
10	284.3	83.3	10,365	8925	1440	17,280

[a]Monthly charge to consumer based on regular contract (c) rates.
[b]Monthly charge to consumer based on variable time zone contract rates.

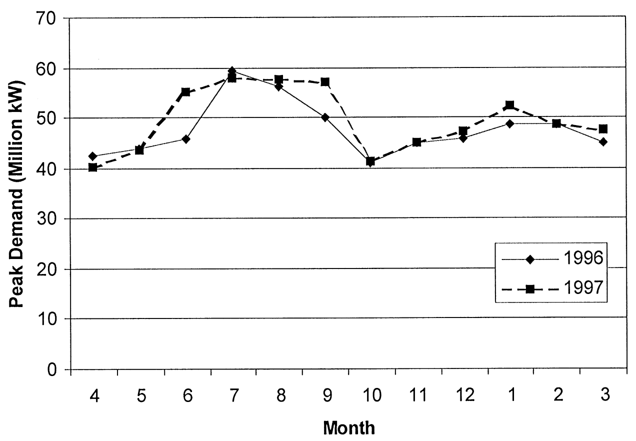

Fig. 1. Monthly peak load in TEPCO service region, 1996 & 1997 Source: TEPCO, 1999.

assumed that the EDV is always charged during the night. Here, the electricity consumption for EDV is calculated using efficiency of 10 km/kWh. The result shows that to the average EDV owner in Japan, the annual economic benefit of switching from a regular contract to a variable time zone contract is 17,280 yen ($US 144) if the EDVs are charged during 11 p.m.–7 a.m. Of more relevance to our analysis is the additional benefit that the vehicle owner can charge the EDV at 6.15 yen/kWh and sell it at the peak rate of 33.7–68.5 yen/kWh (explained later). The high rate for on-peak sales is essential to use EDVs as economically competitive peak power sources.

4.2. Dispatch season

Fig. 1 shows the peak demand for each month in 1996 and 1997. Since EDVs will only be used for peak shaving, the utility will only need EDVs to be available during the summer and a portion of the winter. Through this analysis, we will assume that EDVs will be under contract during June, July, August, September, and January, and provide peak power on 3–10 days per month. This will be 15–50 days a year, and assuming a 4-hr dispatch period, an annual load factor of 0.7–2.3%.

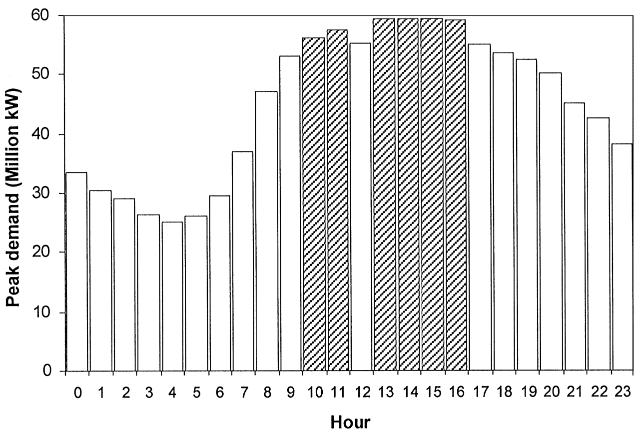

Fig. 2. Load shape of the peak day in 1996 (potential EDV dispatch hours indicated in gray). Source: TEPCO (1999).

4.3. Dispatch hours

Fig. 2 shows the hourly load shape of the peak day in 1996. In general[5], peaks occur for 2 hr before and 4 hr after lunch break. It is possible to have half the target fleet discharge before noon for 2 hr and half for 4 hr after noon, or one-third of the fleet discharging 2 hr each to cover the 6-hr peak period. However, the analysis for the TEPCO region is not sensitive to the number of dispatch hours which makes it significantly different from Kempton and Letendre's peak analysis (1997). This is because the purchase rate for individual power producers (IPPs) for TEPCO (described in detail later) is based on energy capacity, in kWh, and not in power capacity, in kW.

4.4. Electrical hookup

We assume the following about the electrical hookup. The hookup would allow charging from the grid as well as discharge back to the grid. Battery EDVs must be grid-charged and thus must be grid-connected. We assume that hybrid vehicles would also have a grid connection to be used as we propose here. Some current hybrid vehicle designs include grid recharging as a convenience to the driver and to enable ZEV mode operation (Ronning, 1997). In the system we propose, timing of discharge would be controlled by the utility. The vehicle owner would set limits on discharge, in units relevant to his or her driving cycle. Such controls are critical to user acceptability for battery EDVs, and are specified in more detail in Kempton and Letendre (1997). We will show below that, given typical vehicle electrical storage and typical driving cycles, substantial reserve power would be left available in battery-EDVs. For the hybrid EDVs, remaining battery capacity is of little practical concern

[5] Considering load shape of other years. See TEPCO (1999).

Table 6
Available electric capacity for 4-hr discharge, after daily travel and range buffer

Electric-drive vehicle	Remaining electric capacity, by daily distance traveled (including a 16 km range buffer)			
	Energy (kWh)		Power (kW)(for 4 hr discharge)	
	16 km	32 km	16 km–4 hr	32 km–4 hr
GM EV1, (Pb/acid)	11.24	9.64	2.81	2.41
Toyota RAV4L EV (NiMH)	17.09	15.72	4.27	3.93
Nissan Altra (Lithium-ion)	27.18	24.82	6.80	6.20
Nissan Altra/CARB projections (lithium-ion)	28.11	26.67	7.03	6.67
Toyota Prius/projected (hybrid-NiMH)	3.56	3.56[a]	0.89	0.89

[a]Hybrid vehicles do not require battery charge to achieve range, since they can run on the internal motor-generator and recharge while driving.

because, once started, the on-board motor-generator can be used if the battery is low.

As described earlier, we will assume a base-load contract of 10 kW. A production vehicle intended for selling power would need a safe external tap for its AC power and a controller to match frequency, phase, and to insure safety interlocks. Based on experience with a prototyped device from Wavedriver Ltd. in the UK, the production cost of these additions is estimated to be 30,000 yen ($250) (Kempton and Letendre, 1997). This figure is added to our present-value calculations later.

4.5. Calculations for available capacity

Table 6 provides capacity an EDV owner could make available to their electric utility. These available capacities, in kWh and kW, are calculated from the technical characteristics of the storage system, vehicle efficiency, consumers' perceived range buffer requirements, and the daily distance traveled (see below), using Eqs. (1) and (2). A 4-h need for power is assumed as an example. A discharge loss factor of 0.9 is also considered assuming a 10% loss when discharging from battery and converting to grid power.

The electrical energy capacity (kWh) available from EDVs is calculated from Eq. (1),

$$EC = \{TES \times DOD - (RB + CD)/EFF\} \times DF, \quad (1)$$

where EC is the energy capacity (kWh), TES the total energy storage capability of the EDV (kWh), DOD the depth of discharge permissible (% fraction), RB the range buffer of extra reserve distance (km), CD the commute distance (km), EFF the efficiency of electric drive (km/kWh), and DF the discharge loss factor (0.9).

The electrical power capacity (kW) available from EDVs:

$$PC = EC/DH, \quad (2)$$

where PC is the power capacity (kw), and DH the number of discharge hours

Table 7
Annual cost to the vehicle owner from peak management

Electric-drive vehicle	Cost by number of times/year the stored energy is accessed (yen)		
	15 times	25 times	50 times
GM EV1, (Pb/acid)	12,326	20,544	41,088
Toyota RAV4L EV (NiMH)	14,187	23,645	47,291
Nissan Altra (lithium-ion)	15,607	26,012	52,023
Nissan Altra/CARB projections (lithium-ion)	7838	13,063	26,125
Toyota Prius/projected (hybrid - NiMH)	3468	5780	11,560

Our required range estimates are based on US data due to difficulty in obtaining Japanese specific driving ranges. Research suggests that 32 km is a sufficient "range buffer" to satisfy 70% of US drivers (Kurani *et al.,* 1994, p. 251). In the US, the average commute is (coincidentally) also 32 km (Pisarski, 1992). For the Kanto region, approximately half of the population lives in urban areas, for whom, as discussed earlier, the range buffer and the weekday commute are, on average, both zero. In the rural areas, we assume the US figures. Since half the population is urban, we simplify the following calculations by using 16-km for both range buffer and average commute.

5. The cost of discharge to the vehicle owner

Eq. (3) is used to determine the cost to the vehicle owner for allowing access to the stored energy in their vehicle. Table 7 presents the expected costs to the vehicle owner based on the number of times the stored energy is accessed during a given year.

$$CY = EC \times DY \times (BD + ER), \quad (3)$$

where CY is the cost per year, EC the energy capacity, DY the number of dispatches per year, BD the cost of battery degradation, ER the electricity rate (6.15 yen/kWh).

Table 8
Maximum rates for individual power producers for TEPCO in 1997[a]

Type of generation source	Base			Middle			Peak	
Annual load factor	80%	70%	60%	50%	40%	30%	20%	10%
Maximum rate (yen/kWh)	9.2	10.0	11.2	12.3	14.3	17.4	20.2	33.7

[a]Source: TEPCO (1999)

For the electricity charge rate, we will use 6.15 yen/kWh, which is the night rate for the variable time zone contract explained earlier.

6. Economic benefit to the electric utility

Utilities have investigated the technical and economic feasibility of energy storage plants for load-leveling purposes for quite some time (Duchi *et al.,* 1988). Rather than making assumptions about the value to utilities, in this analysis we will use the rate that TEPCO announced to seek individual power producers (IPPs) in 1997. These announced rates, shown in Table 8, illustrate that TEPCO is willing to pay a premium for power that is drawn on only a small proportion of the time — up to 33.7 yen/kWh.

In 1997, TEPCO sought 1 million kW from IPPs. Although we were not able to obtain TEPCO's cost for avoided capacity and avoided energy separately, it is reasonable to assume that the rates shown in Table 8 reflect the costs for both. Thus, we will use Eq. (4) to estimate the benefit for the utility.

$$\text{Annual value to utility} = \text{avoided energy} \times \text{energy cost rate.} \quad (4)$$

EDV batteries are premium peak power sources that will provide instant power when the utility wants it. If the batteries are accessed by the utility for peak power 4 hr per day, 15–50 days a year, the annual load factor is only 0.7–2.3% (see p. 14). Thus, using a purchase rate of 33.7 yen/kWh (current rate for 10% annual load factor sources) does not truly reflect the value of avoided peak capacity by EDVs. An IPP probably would not build an entire power plant to sell power only 3–5% of the time, which is presumably why the rates do not go below 10%. On the other hand, an EDV owner would be glad to since the vehicle power plant is being bought anyway, for driving. Fig. 3 shows our projected rates for power sources with annual load factors of 5 and 3%, extrapolating from the announced IPP rates in Table 8. The extrapolated values use the equation shown in Fig. 3, which we inferred from the announced rates.

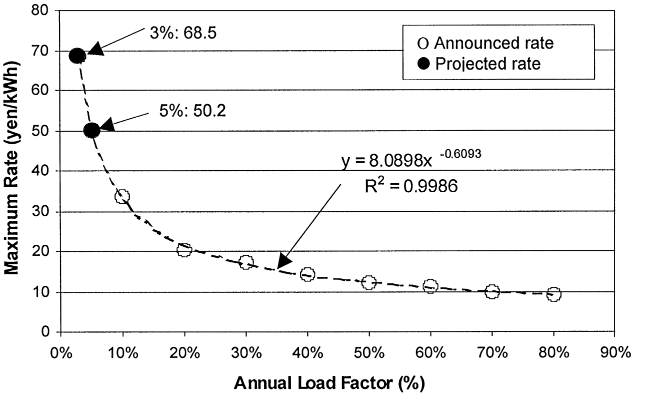

Fig. 3. Estimated rate for 3 and 5% annual load factor.

Table 9 shows the annual economic value to the electric utility of EDV peak power (per vehicle), using the current IPP rate for 10% and projected rate for 5 and 3% load factors. It assumes an annual dispatch of 25 times, a 16-km buffer and a 16-km average daily commute.

7. Cost comparison

Table 10 summarizes the cost comparison between the utility's benefit and the owner's cost, using three purchase rates of peak electricity from EDVs.

The results show that using the rate of 33.7 yen/kWh, and assuming near-term costs as described earlier, only the CARB projected Nissan Altra has economic benefit. By contrast, using a projected rate of 50.2 yen/kWh, the current Nissan Altra is also cost-effective. Using 68.5 yen/kWh the current Toyota RAV4L EV is cost-effective as well. The Toyota Prius hybrid, due to its high storage cost per kWh (due in turn to its high cost per kWh and low recommended depth of discharge), at best is just better than a break-even when analyzed at the highest purchase price for peak electricity. For the better-matched vehicles, the net annual benefits can be substantial, up to 32,000 yen/yr.

7.1. *Net present benefit*

From the numbers in Tables 8 and 9, one can determine the potential utility payment to the customer by discounting the 15 years' worth of annual values to their present value using the utility's weighted-average cost of capital (WACC). For example, assuming avoided capacity costs of our 50.2 yen/kWh scenario and a 7.0% discount rate, the utility could pay up to 295,156 yen ($2,460) as an up-front payment to the owner of a Nissan Altra. For the vehicle owner, the logic would be to discount the stream of annual costs found in Table 7 to their present value. Assuming that the utility would

Table 9
Annual value to utility of EDV peak capacity, by 25 times dispatch annually, with 16km range buffer and 16km average daily commute

Electric-drive vehicle	Avoided energy (kWh)		Total annual avoided cost (yen)		
	Per dispatch	Annual (25 times)	33.7 yen/kWh (10% load factor)	50.2 yen/kWh (5% load factor)	68.5 yen/kWh (3% load factor)
GM EV1 (Pb/acid)	9.64	241.0	8120	12,095	16,505
Toyota RAV4L EV (NiMH)	15.72	393.0	13,244	19,729	26,920
Nissan Altra (lithium ion)	24.82	620.5	20,911	31,149	42,504
Nissan Altra/CARB projections (lithium ion)	26.67	666.7	22,469	33,469	45,670
Toyota Prius/projected (hybrid-NIMH)	3.56	89.1	3003	4473	6103

Table 10
Summary of annual benefit minus cost comparison by three purchase rates

Electric-drive vehicle	Annual benefit to utility minus cost to vehicle owner (yen/year)		
	33.7 yen/kWh	50.2 yen/kWh	68.5 yen/kWh
GM EV1, (Pb/acid)	− 12,424	− 8449	− 4039
Toyota RAV4L EV (NiMH)	− 10,401	− 3917	3275
Nissan Altra (lithium ion)	− 5101	5137	16,492
Nissan Altra/CARB projections (lithium ion)	9406	20,407	32,608
Toyota Prius/projected (hybrid-NiMH)	− 2777	− 1307	323

Table 11
Comparison of net present cost and value of EDVs for peak power

Electric-drive vehicle	Net Present Benefit to Utility minus Net Present Cost to Vehicle Owner Over 15 year period (yen)		
	33.7 yen/kWh	50.2 yen/kWh	68.5 yen/kWh
GM EV1, (Pb/acid)	− 116,201	− 78,529	− 36,749
Toyota RAV4L EV (NiMH)	− 92,274	− 30,829	37,319
Nissan Altra (lithium ion)	− 38,419	58,595	166,192
Nissan Altra/CARB projections (lithium ion)	79,172	183,413	299,026
Toyota Prius/projected (hybrid-NiMH)	− 47,448	− 33,518	− 18,067

require 25 discharges annually and the consumer applied a discount rate of 10%, the cost to the vehicle owner would be 206,562 yen ($1,721) over the 15-year life of the Nissan Altra. For completeness, we include the additional capital cost of the reverse-power connection, which Kempton and Letendre (1997) estimate at 30,000 yen ($250). This would raise the vehicle owner's cost to 236,562 yen ($1,971). Table 11 shows the summary of these calculations, comparing the vehicle owner's cost with the value to the utility.

8. Conclusion

If one assumes the near-term cost of limited-production EDV battery manufacturing, and without any change in current rate structure, we find that electric vehicles cannot profitably sell peak power from their batteries. However, with a small change in rate schedules to allow for low load factors, and the expected decline in battery manufacturing costs with mass-production, we find that some battery EDVs could be very economical sources of peak power, benefiting both the utility and the vehicle owner. The key variables, whether for battery EDVs or hybrid or fuel cell EDVs using smaller battery systems, are cost of battery (per kWh), depth of discharge, and cycle life of battery. Thus, due to its high battery cost, the Toyota hybrid vehicle analyzed showed costs and benefits at best as a break-even, even when assuming an enlarged 5.5 kWh battery. The economics of hybrids could be considerably improved in either of two ways: (1) if the motor-generator were run when the utility needed power, or (2) if the battery were enlarged to permit significant ZEV operation (implying lower cost per kWh storage, as in battery EDVs). An example of such a hybrid is the currently prototyped General Motors' EV1 series hybrid, which has a 67-km range on the battery alone. This type of vehicle thus would offer a substantial advantage over the Toyota parallel hybrid analyzed here.

Government policy could help to realize the potential of EDVs for utility power. Policies could include coordinating auto-manufacturers and electric utilities to overcome infrastructural barriers, setting standards for interconnection, facilitating or funding early deployment of some EDV power connections to gain experience now despite high battery costs, and by providing incentives for large-battery, grid-rechargeable hybrids (for example, considering them as "local-ZEVs"). An economic benefit to EDV buyers, based on the value of storage, would contribute to bringing down EDV prices, further expanding their market and thus reducing urban air pollution. Use of EDVs for utility peak power will make the current electric generators more efficient and, by increasing storage in the electrical system, it will further the market for renewable energy.

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