## Homework 3 Solution

In the solution of problems $1-4$, ignore battery losses with the implication that those losses are considered to be part of the grid losses. A more thorough approach is to assume a battery round-trip efficiency in the $85 \%-95 \%$ to get a more concrete idea. However, for the purposes of this course, that level of detail is not required.

1. An $E V$ has been equipped with a Li-ion battery pack with a $100 \%$ state of charge (s.o.c.) rating of 80 kWh . The $E V$ requires about $200 \mathrm{~Wh} / \mathrm{mi}$ for city driving and $250 \mathrm{~Wh} / \mathrm{mi}$ for modest-speed highway cruising. We wish to analyze the functionality with respect to the $U S$ average round-trip commute distance of 32 miles.
a. For a commute in an urban setting, determine the amount of energy that needs to be recovered at work during the day or at night at home. You need to consider the scenarios in which charging is either available or not available at one of the two locations.
b. Given a specified $C / 5$ recharge rate, calculate the charge time needed for a oneway commute or for the full round-trip commute. Comment on the results if the charger is limited to 1.4 kW output.
c. In the event that the user seeks to refill to at least $80-\%$ s.o.c. over a short time after a daily commute, is daily fast charging required? If so, determine in terms of the $C$-multiple rate required to recover to the $80-\%$ s.o.c. in 10 minutes.

## Solution

a. A 32-mi urban commute uses $200 \mathrm{~Wh} / \mathrm{mi}$ and consumes 6.4 kWh . If charging is available at both locations, then 3.2 kWh at each location replenishes the consumed energy. If either of the locations is without charging, the full 6.4 kWh will be charged at the single location at which charging is available.
b. Since this battery pack capability is 80 kWh , its $C$ rate is 80 kW . A C/5 recharge rate yields 16 kW . The charge time to restore the energy used for the one-way commute at the $16 \mathrm{kWC} / 5$ rate requires 12 min ; for the round-trip restoration, the
charge time takes 24 min . However, if the charger is limited to 1.4 kW - about $C / 60$ - one-way recovery takes about 2 h 20 min , and round trip takes about 4 h 35 min. Such charging durations are acceptable, given expected parking times.
c. The needed charge is 6.4 kWh - merely $8 \%$ of the battery pack capability - so a fast charge appears to be unnecessary. A more comprehensive analysis allows us to consider two scenarios. In one, outlets are easy to find and the driver performs routine overnight charging at low energy costs and low battery stress. In the other scenario, outlets are harder to find, and charging may be performed only once or twice per week. At once per week, the energy consumed is $6.4 \mathrm{kWh} \times 5$ days $=$ 32 kWh ( $40 \%$ of s.o.c.) and the battery retains 48 kWh . In the latter case, to restore to $80-\%$ s.o.c., i.e., 64 kWh , the driver seeks 16 kWh (20 \% of s.o.c.) over ten minutes. The $C$ rate is 80 kW . A charge of 16 kWh in 10 min requires a rate of 96 $k W$, or 1.2 C. A fast charger is required in this case and probably without too much stress on the battery pack.
2. A large truck is equipped with a $700-\mathrm{kWh}$ battery pack and consumes about $2,500 \mathrm{~Wh} / \mathrm{mi}$ for highway cruising. Truck drivers must take breaks of at least 30-min duration after driving a maximum of $8 h$. Moreover, they are allowed to drive only $11 h$ during a $14-h$ total shift. The driver must then be off-duty for the remaining $10 h$ in a $24-h$ day.
a. Determine the distance this truck travels between breaks, given that none of the following constraints may be violated:

- $8 h$ maximum continuous operation
- 70 mph maximum speed
- keep s.o.c. at or above $20 \%$

Which of these constraints is the most restrictive and is met ahead of either of the other two constraints and, therefore, becomes binding?
b. Compute the charge rate required to recover all of the energy use if charging is possible for all 3 hours of the required breaks?
c. Determine the charge rate required to make use of all the downtime and without the violation of the constraints in part (a) to restore full range every 24 hours?

## Solution

a. To determine the most severe constraint, we know that 8 hours of non-stop driving at 70 mph to cover 560 mi consumes $1,400 \mathrm{kWh}$ and so is impossible. The 20 \% s.o.c. constraint implies that 560 kWh energy capability may be used adequate energy for 224 mi of travel over 3 h and 12 min . The driver needs to stop and recharge after, at most, this time duration. It appears that the driver can reach a distance of $70 \mathrm{mi} \times 11 \mathrm{~h}=770 \mathrm{mi}$ in a day, but extremely fast charging is required since the vehicle needs to recharge more than 3 times to reach 770 mi .
b. The maximum range with unconstrained recharge is 770 mi to replenish the consumed energy of $770 \mathrm{mi} \times 2,500 \mathrm{~Wh} / \mathrm{mi}=1,925 \mathrm{kWh}$. The delivery of this energy in $3 h$, requires power delivery at 642 kW - about 0.92 C for the nominal $700-k W h$ capability of the battery. The charger needs to be large with high power level, but, overall, the battery may tolerate the associated stress.
c. The best-case scenario uses fast charging only when it is absolutely required. The consumed energy is $1,925 \mathrm{kWh}$, but we want the vehicle to arrive at the end of the day with only 20 \% s.o.c.. An overnight charge of 560 kWh , and ideal fast charging during the drive requires $1,925-560=1,365 \mathrm{kWh}$ to be restored during the $3 h$ of breaks, with 560 kWh during the remaining 10 hours. The 1,365 kWh allocation into $3-h$ periods requires that $1365 / 3=455 \mathrm{kWh} / \mathrm{h}-$ i.e., at 0.65 C , at the three rest stops. The overnight 560 kWh charge implies that the charge rate is $560 / 10=56 \mathrm{kWh} / \mathrm{h}-$ i.e., at 0.08 C during the overnight stop.

As you may imagine, in a highway setting with thousands of trucks seeking to manage their charging needs in an hour will result in massive energy and power demands at each charging location - a major challenge that must be addressed.
3. Li-ion battery range, in effect, the energy capability, at $0^{\circ} \mathrm{C}$ is about $60 \%$ of the value at $25^{\circ} \mathrm{C}$. This temperature impacts the effective battery pack capability and also affects the $C$ rate: a cold battery needs to be charged considerably more slowly than a warm one. Repeat the problem 1. above for a low-temperature commute with the same $E V$. However, assume that the cabin heat load consumes an additional $50 \mathrm{~Wh} / \mathrm{mi}$ for the commute.

## Solution

a. In this case, the vehicle has reduced capability of 48 kWh and consumes 250 $W h / m i$ in its urban commute. The one-way energy required rises to $4 k W h$ and the round trip is 8 kWh .
b. $\quad C / 5$ becomes, in this case, a rate of 9.6 kW . As the one-way trip requires 25 min and the round trip requires 50 min . At 1.4 kW , the charging times become 2 h 52 $\min$ and $5 h 43 \mathrm{~min}$, which are still quite reasonable within time spent in the workplace parking lot.
c. $\quad 8 \mathrm{kWh}$ is $1 / 6$ of the battery pack capability, so the general conclusion holds: as long as outlets are easy to access, low-rate daily charging is fine. Indeed, weekly charging of 40 kWh is a distinct possibility. We did not cover in the lecture, but a careful current sequence is key to raise gradually the battery temperature. During fast charge, the temperature is considerably higher and the rates are more along the lines of the solution to problem 1.
4. A hypothetical battery offers double of both the energy density and the power density compared to a widely available Li-ion-cell-based battery pack. Based on your analysis and results in the solution of the problems above, comment on the impacts of such a technology. Carry out your analysis under the assumption that the costs per $k W h$ of the technology is double that of Li-ion technology.

## Solution

In the commuter car application, it is difficult to see much impact, as long as outlets are convenient. The $80-k W h$ battery pack seems very large, and a larger one - even without a mass increase - seems to add minimal benefits. It seems unlikely that the doubled costs can be easily and effectively managed.

In the truck application, the doubled battery capability can make a considerable difference. A truck driver's ability to go 6 hours between breaks makes it much easier to schedule meals and other more natural break times. The grid impacts are about the same, but the effective $C$ rates will be modest and battery life could become longer.

