Specific power limitation

The ability of a battery to deliver and accept energy at very high rates is limited by the physical processes occurring within the battery cells. When current flows into the battery, the reaction within the cell must occur at a corresponding rate[1]. This means that the dynamics of the reaction at the electrode surface and the transport of ions (kinetic properties) must occur at the same rate as the supplied current. Because of the high currents associated with high power, the reaction rate is unable to match the rate at which current is being supplied. As a result, the capacity of the battery is reduced and joule heating occurs within the cell.

Specific energy limitation

The restricted energy content of batteries is one of the major drawbacks limiting the successful implementation of EV technology. Considering the specific energy of gasoline is 9.2kWhkg^{-1} corresponding to more than 3kWhkg^{-1} useful specific energy[2], limitations of the battery powered EV become apparent. Two emerging battery technologies addressing the specific energy limitations are lithium air (Li-air) and lithium flour (Li-flour).

Summary of equations

1. Nominal energy capacity (E_{nom}, in Wh or kWh): It is the maximum amount of electrical energy that can be extracted from a fully charged battery state to the empty state.
2. Nominal voltage (V_{nom}, in V) : It is rated voltage of the battery when it is fully charged. When a battery is discharged or is loaded, the voltage reduces gradually to a lower value, V_{batt} .
3. Nominal current (I_{nom}, in A) : It is rated current of the battery for charging or discharging. Typically, the actual charging/discharging current $I_{batt} <= I_{nom}$.
4. Nominal power (P_{nom}, in W) : It is rated power of the battery for charging or discharging derived as a product of the nominal voltage and current of the battery. $P_{nom} = I_{nom} V_{nom}$
5. Energy density or specific energy (Wh/L or Wh/kg): It is the capacity of the battery per unit volume or unit weight.
6. Ampere-hour (Q_{nom}, in Ah): An ampere hour is a unit of electric charge that corresponds to the charge transferred by a steady current of one ampere flowing for one hour, or 3600 coulombs. The commonly seen milliampere hour (mAh) is one-thousandth of an ampere hour (3.6 coulombs). $E_{nom} = Q_{nom} V_{nom}$
7. State of charge, SOC (B_{SOC}, in %): The battery state of charge (SoC) is defined as the ratio between the amount of energy currently stored in the battery, E_{batt} and the total battery capacity, E_{nom}.
   $B_{SOC} = (E_{batt} / E_{nom})100$

8. Coulombic Efficiency (ηC in %): The Coulombic efficiency is the ratio between the discharge and charge capacity. The efficiency of a battery is not always constant and it depends on the SOC, cell temperature, lifetime and current. If $I_{ch}(t)$ and $I_{disch}(t)$ are the charging and discharging currents.
   $\eta C = 100(\int I_{ch}(t)dt)/ \int I_{disch}(t)dt.$
9. Energy Efficiency (η_E in %): The energy efficiency is the ratio between the discharge and charge energy. If $I_{ch}(t), V_{ch}(t)$ and $I_{disch}(t)$, $V_{disch}(t)$ are the charging and discharging currents and voltages as a function of time, respectively,
   $\eta_E = 100 * (\int I_{disch}(t)V_{disch}(t)dt)/(\int I_{ch}(t)V_{ch}(t)dt)$ $\eta_E = 100 * E_{disch}/E_{disch}$,
   where $E_{ch} E_{disch}$ are the energy delivered to the battery during charging and energy extracted from the battery during discharging, respectively.
10. Charge/Discharge rate (C-rate): It is the ratio of the magnitude of current drawn/fed to the battery, to the nominal ampere-hour of the battery.
   $C\text{-}rate = (I_{ch}/Q_{nom})$

Hybrid energy storage

One method of achieving electrical energy storage with a high specific power is to use ultracapacitors (UC)[3]. The use of UC's alone would not suffice, as these components display poor specific energy characteristics. The ideal solution is to use a hybrid energy storage method in a parallel configuration as shown in the figure. This type of set up combines the high specific power density of UC's with the higher specific energy of an electrochemical battery (B).

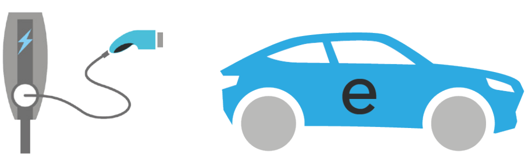


Figure (a) shows the case for a low power demand, where B is able to charge the UC.

(a)

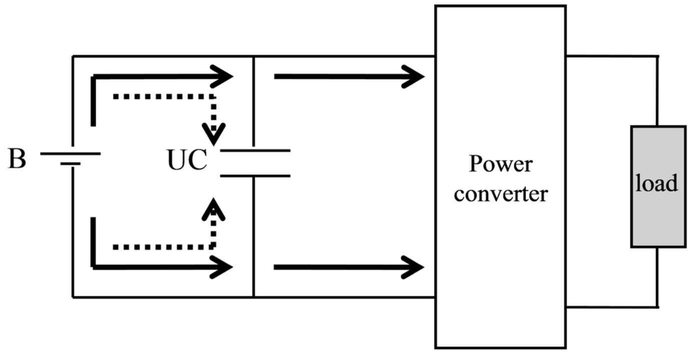
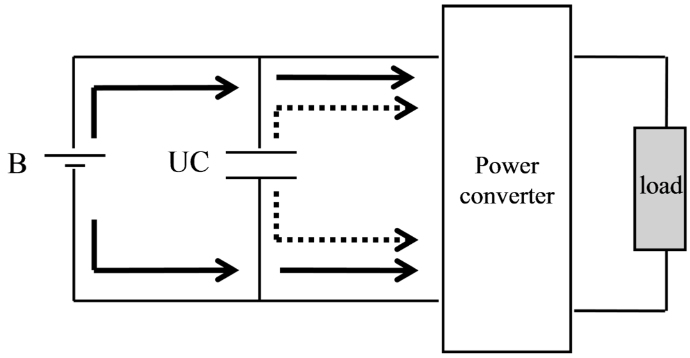


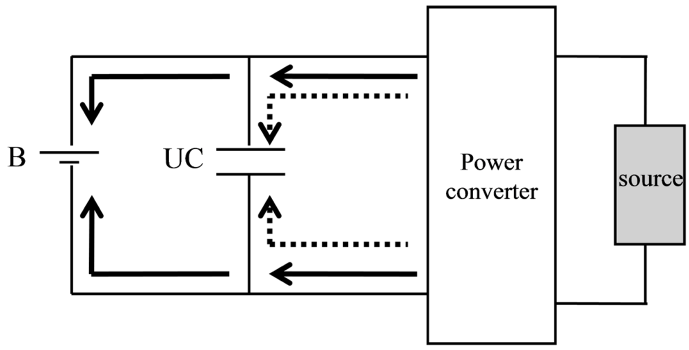
Figure (b) shows the case where a higher power is demanded and both B and UC contribute to the total power supply.

(b)



Both energy storage sources can be recharged using regenerative braking, as shown in Figure (c).

(c)



This type of configuration is however more costly, due to the additional components and the additional complexity in controlling and managing both power sources. This cost could be offset by selecting a battery technology which has high specific energy, as specific power is no longer a requirement to fulfill.

Range testing

Although car manufacturers often advertise both the range of the EV and its battery capacity (in kWh), consumers tend to be mostly concerned with the range. To standardize the advertised range of an EV, both the EU and the US have developed their own method of determining the 'real world' range of an EV.

In the United States, the governmental Environmental Protection Agency (EPA) is in charge of fuel economy tests. The last major update to its techniques was in 2008, and in 2017 there has been an update for cars from that year onward. The test goes through five cycles emulating 'average driving': city, highway, high speed, A/C, cold temperature.

In a laboratory, the car is placed on a dynamometer, which is a sort of treadmill for cars. Through adopting the rotational resistance of the rollers, the influence of wind can be emulated. The entire cycle as shown on the EPA website is shown in the table on the next page.

Test cylce Attribute	Test cycle				
	City	Highway	HIgh speed	A/C	Cold temp
Trip type	Low speeds in stop-and-go urban traffic	Free-flow traffic at highway speeds	Higher speeds; harder acceleration & braking	A/C use under hot ambient conditions	City test w/ colder outside temp.
Top speed	56 mph	60 mph	**80 mph**	54.8 mph	56 mph
Average speed	21.2 mph	48.3 mph	48.4 mph	21.2 mph	21.2mph
Max. acceleration	3.3 mph/sec	3.2 mph/sec	**8.46 mph/ sec**	5.1 mph/sec	3.3 mph/sec
Simulated distance	11 mile	10.3 mile	8 mile	3.6 mile	11 mile
Time	31.2 min	12.75 min	9.9 min	9.9 min	31.2 min
Stops	23	None	4	5	23
Idling time	18% of time	None	7% of time	19% of time	18% of time
Engine startup*	**Cold**	Warm	Warm	Warm	**Cold**
Lab temperature	68°F-86°F			**95°F**	**20°F**
Vehicle airconditioning	Off	Off	Off	**On**	Off

**A vehicle's engine doesn't reach maximum fuel efficiency until it is warm.*

In Europe, the New European Drive Cycle (NEDC) is the standard for vehicle fuel economy testing. In spite of the name, it has been last updated in 1997, and it has been repeatedly criticized for portraying fuel economies that are non-achievable in real-world driving.

The test goes through two different cycles. The first cycle is an urban drive cycle that is repeated four times, and the second cycle which completes the test is called the extra-urban drive cycle.

The difference in methodology between these two tests can lead to range estimates that vary 17%, with the EPA rating having the more conservative and realistic estimation.

References

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3. Guidi, G., T.M. Undeland, and Y. Hori, *Effectiveness of Supercapacitors as Power-Assist in Pure EV Using a Sodium-Nickel Chloride Battery as Main Energy Storage,* in EVS24. 2009: Stavanger, Norway