Battery University

BU-1003: Electric Vehicle (EV)

Discover alternatives to fossil fuel in batteries

Transformation from the horse-drawn carriage to horseless transportation took its time when new technology arrived. The architecture and seating arrangements stayed the same for a while on early cars; only the horse was replaced with a motor. Figure 1 illustrates proud and well-to-do travelers on a horseless carriage, well elevated from the danger of horse's hoofs and the grit from the street.

Figure 1: Horseless carriage.
Architecture seating arrangements are slow to change when new technology arrives.
Open source

In the early 1900s, the electric vehicle was reserved for dignitaries the likes of Thomas Edison, John D. Rockefeller, Jr. and Clara Ford, the wife of Henry Ford. They chose this transportation for its quiet ride over the vibrating and polluting internal combustion engine. Environmentally conscious drivers are rediscovering the EV with a choice of many attractive products.

The EV culture is developing distinct philosophies, each satisfying a unique user group. This is visible with vehicle sizes and the associated batteries. The subcompact EV comes with a battery that has 12–18kWh, the mid-sized family sedan has a 22–32kWh pack, and the luxury models by Tesla stand alone with an oversized battery boasting 60–100kWh to provide extended driving range and achieve high performance.

The EV is said to replace cars with the internal combustion engine (ICE) by ca. 2040. Several technological improvements will be needed to make the electric powertrain practical and economical. Even with oil at $100 a barrel, the price of the EV batteries would need to fall by a factor of three and also offer ultra-fast charging. In terms of carbon footprint, the electricity used to power the EVs would need to come from renewable sources. Published reports say that emissions from EVs powered by America's electricity grids are higher than those from an efficient ICE. Table 2 illustrates common EVs.

Model	Battery	Charge Times
Toyota Prius PHEV	4.4kWh Li-ion, 18km (11 miles) all-electric range	3h at 115VAC 15A; 1.5h at 230VAC 15A
Chevy Volt PHEV	16kWh, Li-manganese/NMC, liquid cooled, 181kg (400 lb), all electric range 64km (40 miles)	10h at 115VAC, 15A; 4h at 230VAC, 15A
Mitsubishi iMiEV	16kWh; 88 cells, 4-cell modules; Li-ion; 109Wh/kg; 330V, range 128km (80 miles)	13h at 115VAC 15A; 7h at 230VAC 15A

Model	Battery	Charge Times
Smart Fortwo ED	16.5kWh; 18650 Li-ion, driving range 136km (85 miles)	8h at 115VAC, 15A; 3.5h at 230VAC, 15A
BMW i3 Curb 1,200kg (2,645 lb)	22kWh (18.8kWh usable), LMO/NMC, large 60A prismatic cells, battery weighs 204kg (450 lb) driving range of 130–160km (80–100 miles)	~4h at 230VAC, 30A; 50kW Supercharger; 80% in 30 min
Nissan Leaf*	30kWh; Li-manganese, 192 cells; air cooled; 272kg (600 lb), driving range up to 250km (156 miles)	8h at 230VAC, 15A; 4h at 230VAC, 30A
Tesla S* Curb 2,100kg (4,630 lb)	70kWh and 90kWh, 18650 NCA cells of 3.4Ah; liquid cooled; 90kWh pack has 7,616 cells; battery weighs 540kg (1,200 lb); S 85 has up to 424km range (265 mi)	9h with 10kW charger; 120kW Supercharger, 80% charge in 30 min
Chevy Bolt Curb 1,616kg; battery 440kg	60kWh; 288 cells in 96s3p format, EPA driving rate 383km (238 miles); liquid cooled; 200hp electric motor (150kW)	40h at 115VAC, 15A; 10h at 230VAC, 30A 1h with 50kWh

Table 2: Electric vehicles with battery type, range and charge time.
* In 2015/16 Tesla S 85 increased the battery from 85kWh to 90kWh; Nissan Leaf from 25kWh to 30kWh.

The makers of Nissan Leaf, BMW i3 and other EVs use the proven lithium-manganese (LMO)battery with a NMC blend, packaged in a prismatic cell. (NMC stands for nickel, manganese, cobalt.) Tesla uses NCA (nickel, cobalt, aluminum) in the 18650 cell that delivers an impressive specific energy of 3.4Ah per cell or 248Wh/kg. To protect the delicate Li-ion from over-loading at highway speed, Tesla over-sizes the pack by a magnitude of three to four fold compared to other EVs.

The large 90kWh battery of the Tesla S Model (2015) provides an unparalleled driving range of 424km (265 miles), but the battery weighs 540kg (1,200 lb), and this increases the energy consumption to 238Wh/km (380Wh/mile), one of the highest among EVs. (See BU-1005: Fuel Cell Vehicle.)

In comparison, the BMW i3 is one of the lightest EVs and has a low energy consumption of 160Wh/km (260Wh/mile). The car uses an LMO/NMC battery that offers a moderate specific energy of 120Wh/kg but is very rugged. The mid-sized 22kWh pack provides a driving range of 130–160km (80–100 miles). To compensate for the shorter range, the i3 offers REX, an optional gasoline engine that is fitted on the back. Table 3 compares the battery size and energy consumption of common EVs. The range is under normal non-optimized driving conditions.

EV make	Battery	Range km (mi)	Wh/km (mi)	Energy cost/km (mi)
BMW i3	22kWh	135km (85)	165 (260)	$0.033 ($0.052)
GM Spark	21kWh	120km (75)	175 (280)	$0.035 ($0.056
Fiat 500e	24kWh	135km (85)	180 (290)	$0.036 ($0.058)
Honda Fit	20kWh	112km (70)	180 (290)	$0.036 ($0.058)
Nissan Leaf	30kWh	160km (100)	190 (300)	$0.038 ($0.06)
Mitsubishi MiEV	16kWh	85km (55)	190 (300)	$0.038 ($0.06)
Ford Focus	23kWh	110km (75)	200 (320)	$0.04 ($0.066)
Smart ED	16.5kWh	90km (55)	200 (320)	$0.04 ($0.066)
Mercedes B	28kWh (31.5)*	136km (85)	205 (330)	$0.04 ($0.066)
Tesla S 60	60kWh	275km (170)	220 (350)	$0.044 ($0.07)
Tesla S 85	90kWh	360km (225)	240 (380)	$0.048 ($0.076)

Table 3: Estimated energy consumption and cost per km/mile of common EVs. Energy cost only includes the consumed electricity at $0.20/kWh; service items are excluded.
* Driving range limited to 28kWh; manual switch to 31.5kWh gives extra 16km (10 mile) spare

Clarification: The driving ranges in Tables 2 and 3 differ. This is less of an error than applying different driving conditions. Discrepancies also occur in topping charge, depth of discharge and fuel-gauging.

The cost of an EV battery has come down to about $350/kWh, but Tesla managed to lower the price to $250/kWh using the 18650, a popular cell of which 2.5 billion were made in 2013. The 18650 in the current Tesla models is an unlikely choice as the cell was designed for portable devices such as laptops. Available since the early 1990s, the 18650 cell is readily available at a low cost. The cylindrical cell-design further offers superior stability over the prismatic and pouch cell, but the advantage may not hold forever as prismatic and pouch cells are improving. Large Li-ion cells are relatively new and have the potential for higher capacities and lower pack-cost as fewer cells are needed.

Prices are dropping and Bloomberg (December 2017) says that the average EV battery costs now $209 per kWh. This includes housings, wiring, BMS and plumbing, housekeeping that adds 20 percent to 40 percent to cell costs. Experts predict that the EV battery will drop below $100 per kWh by 2025. This will put the EV in par with a conventional powered vehicle of similar features. These price reductions do not apply to stationary battery systems that, according to Bloomberg, will command a 51

All EV makers must provide an 8-year warranty or a mileage limit on their batteries. Tesla believes in their battery and offers 8 years with unlimited mileage. Figure 4 illustrates the battery that forms the chassis of the Tesla S Model. The Model S 85 contains 7,616 type 18650 cells in serial and parallel configuration. The smaller S-60 has 5,376 cells.

Figure 4: Battery in a Tesla S Model chassis. The 85kWh battery has 7,616 18650 cells in parallel/serial configuration. At $250 per kWh, the cost is lower than other Li-ion designs.
Source: Tesla Motors

EV manufacturers calculate the driving range under the best conditions and according to reports, the distances traveled in the real-world can be 30–37 percent less than advertised. This may be due to the extra electrical loads such as headlights, windshield wipers, as well as cabin heating and cooling. Aggressive driving in a hilly countryside lowers the driving range further.

Cold temperature also reduces the driving range. What battery users may also overlook is the difficulty of charging when cold. Most Li-ion cannot be charged below freezing. To protect EV batteries, some packs include a heating blanket to warm the battery during cold temperature charging. A BMS may also administer a lower charge current when the battery is cold. Fast charging when cold promotes dendrite growth in Li-ion that can compromise battery safety. (See BU-410: Charging at High and Low Temperature)

EV owners want ultra-fast charging and technologies are available but these should be used sparingly as fast charging stresses the battery. If at all possible, do not exceed a charge rate of 1C. (See BU-402: What is C-rate?) Avoid full charges that take less than 90 minutes. Ultra-fast charging is ideal for EV drivers on the run and this is fine for occasional use. Some EVs keep a record of stressful battery events and this data could be used to nullify a warranty claim. (See BU-401a: Fast and Ultrafast Chargers)

Estimating SoC has always been a challenge, and the SoC accuracy of a battery is not at the same level as dispensing liquid fuel. EV engineers at an SAE meeting in Detroit were surprised to learn that the SoC on some new BMS were off by 15 percent. This is hidden to the user; spare capacity makes up for a shortfall.

EV makers must further account for capacity fade in a clever and non-alarming way to the motorist. This is solved by oversizing the battery and only showing the driving range. A new battery is typically charged to 80 percent and discharged to 30 percent. As the battery fades, the bandwidth may expand to keep the same driving range. Once the full capacity range is needed, the entire cycle is applied. This will cause stress to the aging battery and shorten the driving ranges visibly. Figure 5 illustrates three SoH ranges of an EV fuel gauge.

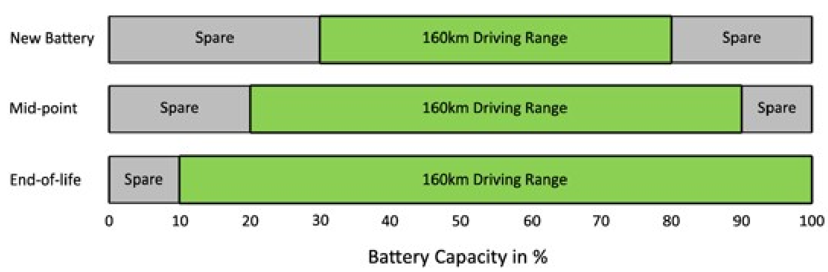

Figure 5: Driving range as a function of battery performance. A new EV battery only charges to about 80% and discharges to 30%. As the battery ages, more of the usable battery bandwidth is demanded, which will result in increased stress and enhanced aging.

Economics

On the surface, driving on electricity is cheaper than burning fossil fuel; however, low fuel prices, uncertainty about battery longevity, unfamiliarity with battery abuse tolerances and high replacement costs are factors that reduce buyer incentives to switch from a proven propulsion system to the electric drivetrain. The EV will always have shorter driving ranges than vehicles with ICE because oversizing the battery has a diminishing return. When the size is increased, batteries simply get too heavy, negatively affecting travel economics and driving range. (See BU-1005: Fuel Cell Vehicle, Figure 1.)

Technology Roadmaps as part of the International Energy Agency (IEA) compares energy consumption and cost of gasoline versus electric propulsion;

An EV requires between 150Wh and 250Wh per kilometer depending on vehicle weight, speed and terrain. At an assumed consumption of 200Wh/km and electricity price of $0.20 per kWh, the energy cost to drive an EV translates to $0.04 per km. This compares to $0.06 per km for a similar-size gasoline-powered car and $0.05 per km for diesel. Price estimations exclude equipment costs, service and the eventual replacement of the product.

According to research, 90 percent of commuting involves less than 30km. The EV market will also include high-end models for the ecology-minded wealthy wanting to reduce greenhouse gases.

Driving an EV only delivers optimal environmental benefit when charging with renewable resources. Burning coal and fossil fuel to generate electricity, as is done in many countries, does not reduce greenhouse gases. In the US, 50 percent of electricity is generated by burning coal, 20 percent by natural gas and 20 percent by nuclear energy. Renewable energy by hydro is 8 percent and solar/wind energy is only 2 percent.

Going electric also begs the question, "Who will pay for the roads in the absence of fuel tax?" Governments spend billions on road maintenance and expansions; the EV, and in part the PHEV, can use the infrastructure for free. This is unfair for folks using public transport as they pay double: first paying income tax to support the road infrastructures and second in purchasing the train fare.

The high cost of the EV against the lure of cheap and readily available fossil fuel will slow the transition to clean driving. Government subsidies may be needed to make "green" cars affordable to the masses, but many argue that such handouts should be directed towards better public transportation, systems that had been ignored in North America since the 1950s.

Guidelines for EV Batteries

- **Life span.** Most EV batteries are guaranteed for 8 years or 160,000km (100,000 miles). Hot climates accelerate capacity loss; insufficient information is available about how batteries age under different climates and usage patterns.
- **Safety.** Concerns arise if the battery is misused and is kept beyond its designated age. Similar fears occurred 150 years ago when steam boilers exploded and gasoline tanks burst. A carefully designed BMS assures that the battery operates within a safe working range.
- **Cost.** This presents a major drawback as the battery carries the cost of a small car powered by an ICE. BMS, battery cooling, heating and the eight-year warranty add to the cost.
- **Performance.** Unlike an ICE that works over a wide temperature range, batteries are sensitive to heat and cold and require climate control. Heat reduces the life, and cold lowers the performance temporarily. The battery also heats and cools the cabin.
- **Specific energy.** In terms of calorific value per weight, a battery generates only 1 percent of what fossil fuel produces. One kilogram (1.4 liter, 0.37 gallons) of gasoline yields roughly 12kWh of energy, whereas a 1kg battery delivers about 150Wh. However, the electric motor is 90 percent efficient while a modern ICE comes in at about 25 percent.
- **Specific power.** The electric propulsion system has better torque with the same horsepower than the ICE. This is reflected in excellent acceleration.

Last updated 2018-08-02

*** Please Read Regarding Comments ***

Comments are intended for "commenting," an open discussion amongst site visitors. Battery University monitors the comments and understands the importance of expressing perspectives and opinions in a shared forum. However, all communication must be done with the use of appropriate language and the avoidance of spam and discrimination.

If you have a suggestion or would like to report an error, please use the "contact us" form or email us at: BatteryU@cadex.com. We like to hear from you but we cannot answer all inquiries. We recommend posting your question in the comment sections for the Battery University Group (BUG) to share.

Or Jump To A Different Article

Basics You Should Know

Comments

On March 14, 2011 at 3:10pm

Bruce Ogilvie wrote:

Concern about storage batteries within residences and industrial/institutional buildings when solar or wind energy conversion systems have been installed. Where can the batteries for a building be safely stored - protected from fire, water, gas release, etc. The use of small WECS or Solar Panels require batteries to level the power. We need to determine the hazard of various storage locations.

On April 7, 2011 at 1:56am

Joachim Solli wrote:

A typical wind turbine is not 30 kV. That was 20-30 years ago. New wind turbines are typically 3-4 MW, old ones around 2 MW.

If one turbine should be 30 kW you will need 1 000 turbines to make 30 MW, and 10 000 to make 300 MW. That would have been a GIGANTIC wind farm.

On June 6, 2011 at 6:33am

Darth wrote:

How is it possible that Sealed Lead-Acid manufacturers claim that their battery life expectancy is 5-10 years when used in Solar or Wind powered Systems and on the other hand they claim that Designated cycle life is around 500 cycles. (500 charging cycles + 500 discharging cycles). If we assume that Sealed Lead-Acid battery will be charged during day and discharged during night it come that 500/365 days will give me 1,36 years of life. When i take in consider that 500 cycles is at 20 degrees Celsius (which is almost never) it come to conclusion that Sealed Lead-Acid will run approximately 1 year… which is i must admit to low comparing to some older chemistries in use. I agree that without particular maintenance such system is very good but on the other hand such system is usually installed far away and on inaccessible terrain and with 1 year of life time it rises a lot of price of such system…

Regards,
Darth

On September 4, 2011 at 7:39pm

Hoolio wrote:

Hi there, I'll try to enlighten you - I work for a Battery manufacturer and I'm involved with solar installs as well.

A VRLA may have a 15yrs 'design' life in normal applications, but only 8 in a solar application due to the cycling and loading.

For life cycle and discharge - Normally a cycle, is 1 full discharge and 1 full charge. Which shouldnt be 24hrs. If it is, yes your 1.36 life is correct.
In remote application a 3, 5 or 7 day backup on a single charge is normally the design factor. And so batterys should be sized accordingly.
I have seen batterys in remote places that are as good as new, many years later.
Also I have seen some allot of batterys exhausted early in their life.
Battery quality and the system design are very critical, to ensuring a long life and care free installation.

If using lead flooded batterys (wet), they must be normalised very month, to maintain the system.

Hope this helps

On December 25, 2011 at 3:57pm

Eduardo wrote:

Does anybody know where can I find the schematic of an electronics circuit to measure the conductivity of a VRLA battery?
I have been looking for on the internet but have not found anything relevant.
I'm trying to build my own batter analyzer.

Merry Christmas!

On June 28, 2012 at 12:33am

Moose wrote:

I can hardly call wind or sun renewable…

On November 4, 2012 at 6:15pm

William Smith wrote:

What about Liquid Metal Batteries? It's the future of this exact topic and there is no mention of the best new invention that will change the world! AMBRI company, look it up…

On July 7, 2014 at 7:22am

what would be the price for storage battery in 1MW & 2MW solar power project

---

On September 4, 2014 at 8:27am

Peter wrote:

I've been using old alcad brand 200ah nicad single cells in a 10x3 12v 600ah bank for a while now. Came out of communication tower setup. Work great. Only off-gas oxygen so need to lube up interconnects or go stainless. Otherwise no memory, rather bulletproof and don't mind overcharging.

On January 1, 2015 at 2:33pm

Jack wrote:

Need to add information on NiFe (sometimes called Edison batteries) chemistry batteries. They are well suited for fixed use, but were used for farm electricity (from windmills) in the 1930's, there were also trucks, locomotives, and Baker electric cars made using them.

They dropped out of favor.

New NiFe batteries and charge controllers are available. They use sodium-hydroxide as the electrolyte. They do have a fairly high daily discharge rate, but they never ware out. Even old ones can be renewed. They also 'learn' by going through charge/discharge cycles to store more power. They are about 1V per cell.

They are also easy to make, but the nickle is currently pretty expensive.

On February 5, 2015 at 4:49am

Louise wrote:

Hi. I'm trying to design a battery back up system for operating rooms only I was wondering if anyone could suggest the best kind of battery for this. It has to be mobile and have the ability to be recharged elsewhere.

On December 29, 2015 at 3:18am

Aditya wrote:

I have few question regarding batteries
1. How a normal car battery is different from battery pack of a hybrid vehicle or an electric vehicle not based on lead acid or Li or metal but rather based AH, voltage ratings charging current.
2. can a car alternator having o/p minimum 50 amps (based on rpm) at 14 volts charge a battery pack of Toyota Prius (Toyota Prius consists of 28 Panasonic prismatic nickel metal hydride modules—each containing six 1.2 volt cells—connected in series to produce a nominal voltage of 201.6 volts.)

Thanks
Aditya

On December 6, 2016 at 8:14am

Ferran wrote:

I see an inconsistency in the Tesla 85 KWh battery data.

You say "The 85kWh battery has 7,616 18650 cells" and "Tesla uses NCA (nickel, cobalt, aluminum) in the 18650 cell that delivers an impressive specific energy of 3.4Wh per cell"

But 3.4Wh x 7616 give 25.9 KWh, not 85 KWh.

So Tesla must have 25.000 cells to achive 85KWh

On January 12, 2017 at 6:28pm

Roderick T.Hall wrote:

How to keep this Samsung phone charge up.

On January 14, 2017 at 8:21am

Jens K Jensen wrote:

The specifications for the Tesla S battery have a few errors. The 85 and 90kWh packs have 7.104 cells (not 7616 which would require 79,333 cells per parallel pack ((7616/16/6 ==79,333 cells in parallel) . Each cell has up to 3,4Ah (6ikely 3,2Ah) or around 12Wh per cell, which does total to somewhere between 81 and 84 kWh.

regards
jensk

On July 27, 2017 at 4:14am

Hugo Barbosa wrote:

Governaments must demand for plug-in batteries packs.
With this, autonomie increase by renting pack/with taxes; batteries management better done by companies; and stress with autonomie doesnt exists.
It haves many others advantages to market, and to automakers and petrol companies

On November 29, 2017 at 8:05pm

Leo wrote:

I'm considering buying a used 2011 Nissan Leaf. It has 40,000 miles on it. I understand that it only has an 8 year warranty (almost up) on the battery and that the range I will be able to drive with it will slowly drop over time. However, what I want to know is, if my trips are REALLY SHORT (less than 15 miles round trip) can I just keep driving it for years and years until it can't make the 15 miles on a single charge? Or will the battery become unstable and dangerous after a certain point and force me to scrap or replace it?
If I'll be forced to scrap/replace it, how far/long should I expect before this occurs?
Thanks!

On December 24, 2017 at 11:44am

Dexterwise wrote:

@Aditya. Youvcant charge hybrid batteries with the alternator as you're saying.

On February 12, 2018 at 10:56am

Craig Nixon wrote:

Would it be possible for an ev battery controller to alter the bandwidth (using your terminology) in winter to maintain the range without affecting longevity. My logic being that the lower temperature may offset the deterioration due to the lower/higher final charge voltage required. I typically loose 20% in winter with final charge of 3.6v. vw panasonic sanyo prismatic cells i believe.

On March 5, 2018 at 2:53am

Morgan Jakobsson wrote:

Chevy Bolt:
The ones who have broken down the battery says it is only marked with 57 kwh on the pack…

https://www.youtube.com/watch?v=N3G8JGsEjPA

https://www.youtube.com/watch?v=ssU2mjiNi_Q

On April 4, 2018 at 8:51pm

Srinath wrote:

I need support to build a prototype 2 seater car in India. Please recommend the type and capacity of battery for a mileage of 100 kms and the fully laden weight would be approximately 500 kgs.