Fundamentals of Electric Vehicles: Technology and Economics
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Lecture 21
Why Lithium Battery – Part 1

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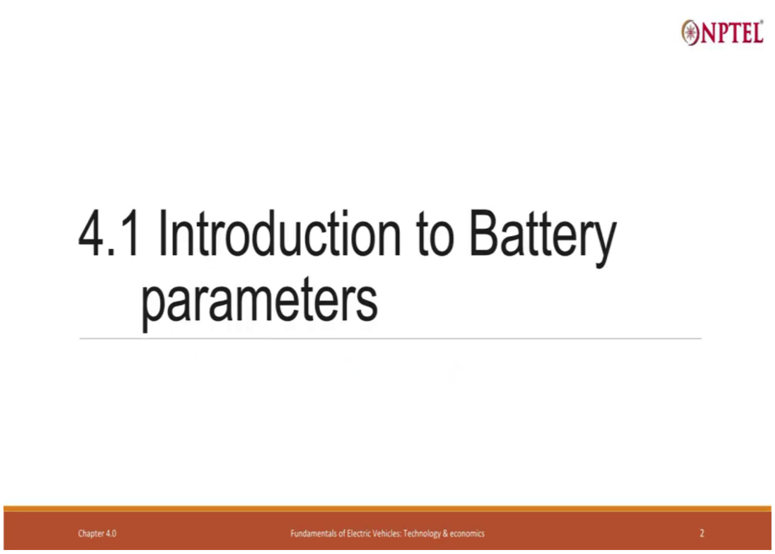

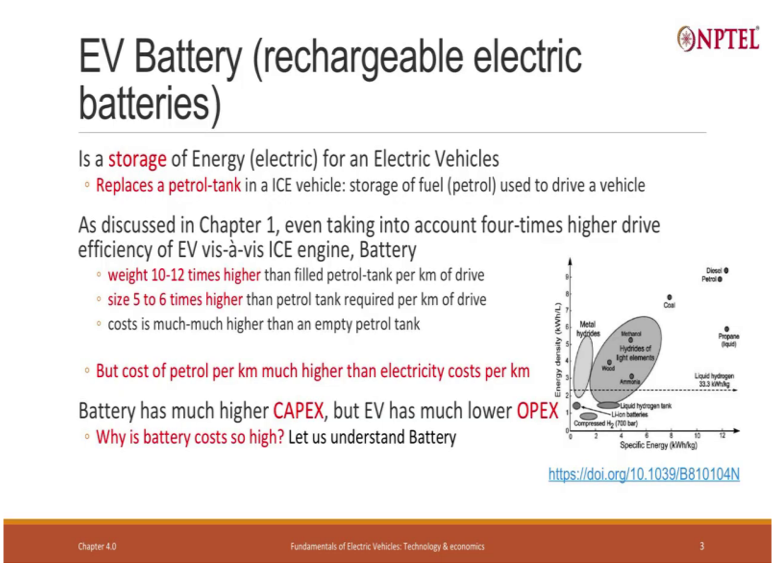

So, we are just we had started in the last class the EV storage, what kind of batteries are used and what are the some of the key important aspect when you start looking at the batteries? We are going to we had looked at and I am just very briefly review at some of the important parameters that govern how good a battery is.

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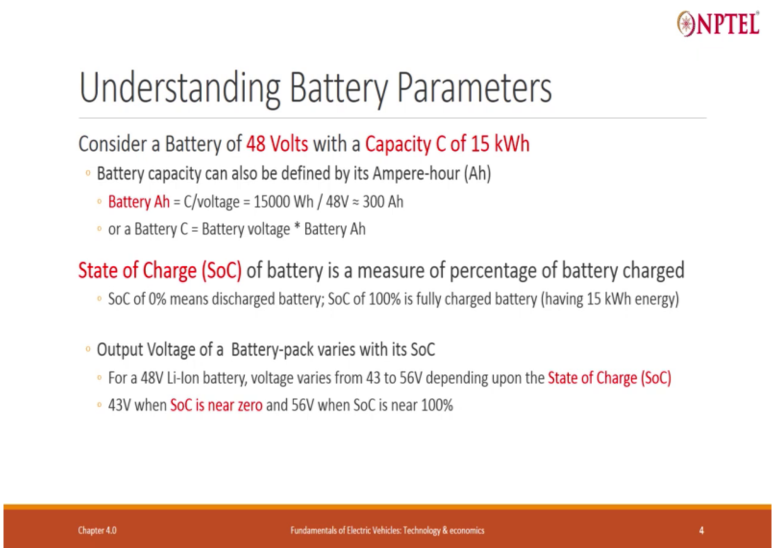

For example, the first thing that you have to ask about the batteries, what is the capacity of the battery? And the capacity of the battery is given in Ah, which is a battery Ah multiplied by the voltage which it uses actually gives you the battery watt hour the total capacity of the battery. So, this is the first thing that I had talked about, then I talked about state of charge of a battery at any point of time what percentage of the battery is charged, well it is a 0 percent basically is battery completely discharged and do it is a 100 percent it is fully charged.

As we will see later on, we never get let the battery go to 0 percent, we never let it go to 100 percent, in both the cases it hurts the battery life if you do that. So, the output voltage if I take a 48 volt battery, it will vary depending on the state of charge of the battery, it can go down to as low as 43 volt, it depends on the way the battery is designed when it is at 0 percent and can go to 55 56 volt when it is close to a 100 percent. So, this is what we have to all the time looking at.

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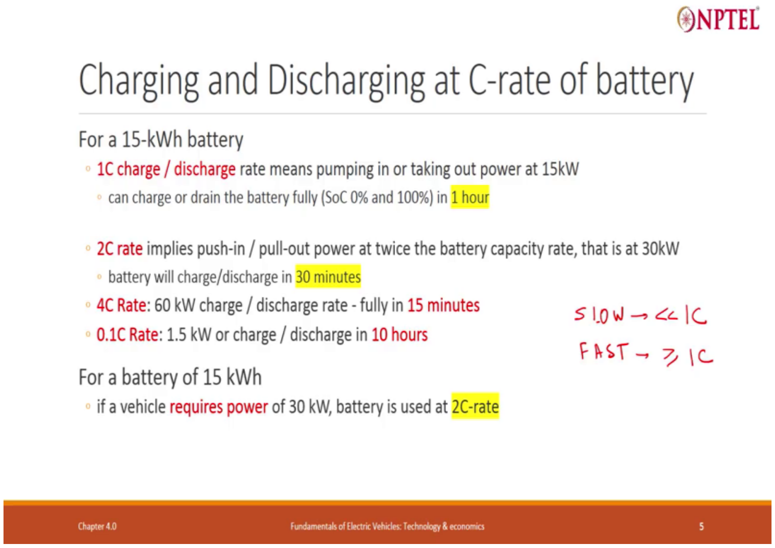

There is a very important concept that I have been talking about repeatedly the C rate of the battery. It is defined as how many C, 1 C, 2 C, 0.5 C, 1 C charging or discharging rate basically means the battery could be charge from 0 percent to 100 percent SOC in 1 hour. So, that is the 1 C, 2 C basically means half the time twice that rate, so actually you can charge from 0 percent to 100 percent in 30 minutes and 0.1 C will mean it will take you 10 hours to charge from 0 percent to 100 percent.

Now, the battery may not be 0 percent to start with and you may not want to charge it 100 percent, well then it will change but if the C rate is defined in that manner, so for example if it is a 15 kilowatt hour battery 1 C charge will be at a charging rate when the power input or output is 15 kilowatt and at 30 kilowatt charging rate it is a 2 C charging.

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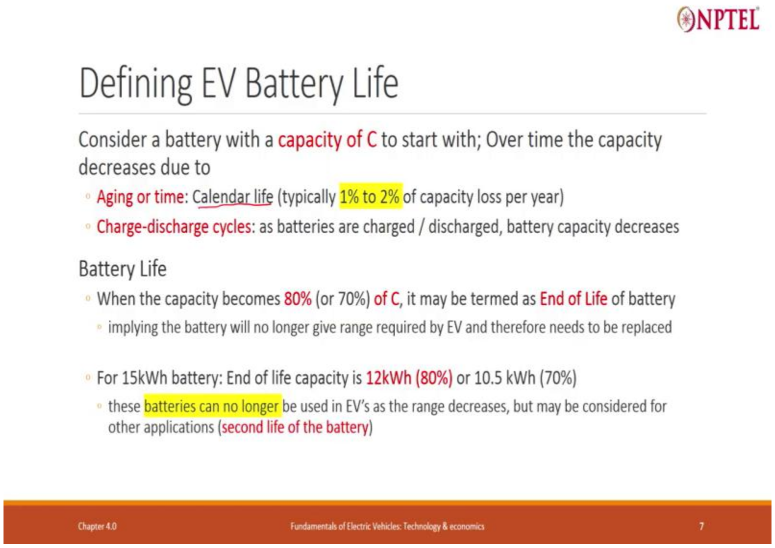

I had talked about how is the capacity of the battery affected and we said there are two important parameters that impacts the capacity of the battery. What is aging with time? As time goes on the battery capacity will slightly deteriorates, does not do too much maybe 1 percent a year, maybe more less, but if you leave the battery it will deteriorate. Similarly, each time we charge the battery discharge this it is called one cycle over, the battery capacity slightly goes down and battery is defined as let us say 2000 cycles it will go from a 100 percent capacity a new battery to 80 percent capacity means the battery capacity has gone down to 80 percent of the initial capacity.

Now, very often when the battery capacity goes down of course it implies that your range that the battery can support for the vehicle will also go down, so very often you do not want to continue to use it. So, very often for a vehicle a end of life can be 80 percent of the initial capacity or maybe 70 percent of the initial capacity. So, the end of life is a very important and that depends on the users want to say now I do not want to work with limited range I would rather replace the battery. So, 15 kilowatt hour battery to begin with and 80 percent basically once it reaches 12.5 kilowatt or for example with 70 percent end of life at 10.5 say battery is no longer usable in electric vehicle.

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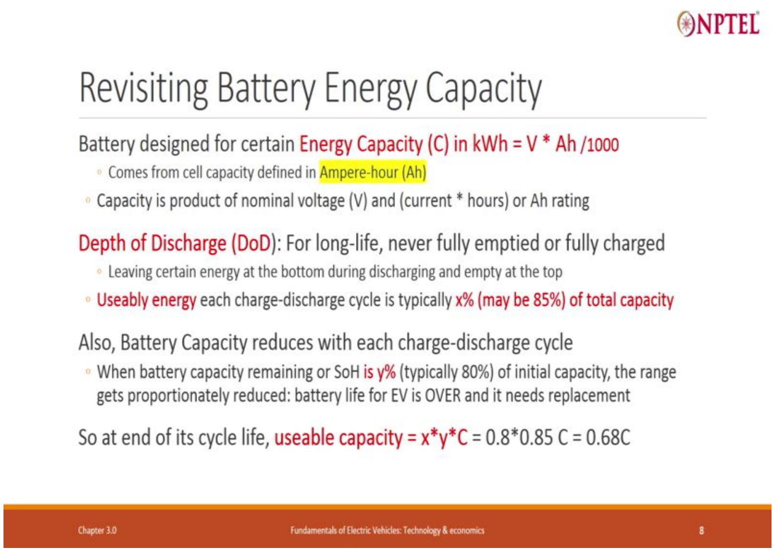

So, this is the battery capacity that we had talked about, the voltage into Ah by 1000 in terms of kilowatt hour. Then we introduced a concept of depth of discharge, remember we said we do not want to charge it to 100 percent or to 0 percent. So, the question is, how far up are you willing to charge? How far low you are willing to discharge? And that depends on a parameter called depth of discharge. For good life of the battery you do not want it to be a 100 percent, probably we have 85 percent 90 percent depends on the battery.

And you may want to leave never reach the top maybe 90 percent maybe even less and similarly do not go to the bottom you want to leave x percent of the total, total energy is the usable energy and some not at the top some not at the bottom. And if the end of life when the battery capacity remaining or state of health, it is the concept of state of health is y percent, that means batteries initial capacity has gone down to y percent, that is the battery life. Then the battery life may be over, so actually the energy available for you at the end of life is only x percent of y percent of the C.

And this is what I told you, so if you make it end of life as 80 percent 85 percent depth of discharge, you are actually at the end of life where the battery capacity is only 0.68 C. So, if in the beginning it gave you a 100 kilo meters now it will only give you 68 kilo meters, so you must keep that in mind, you must keep in mind the end of life and you must keep in mind the depth of discharge.

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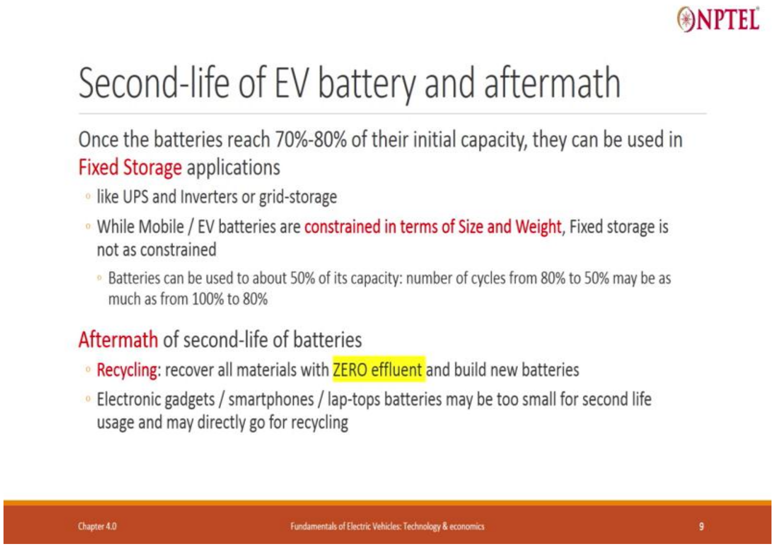

There is a second life of the battery that after the battery capacity has gone down and you no longer want to use in electric vehicle you can still use it somewhere else for example in fixed application where you do not mind the battery size to be little larger, so you actually keep it and for example UPS and all that and of course I had mentioned that aftermath of second life is you want to recycle, we will come to that later on.

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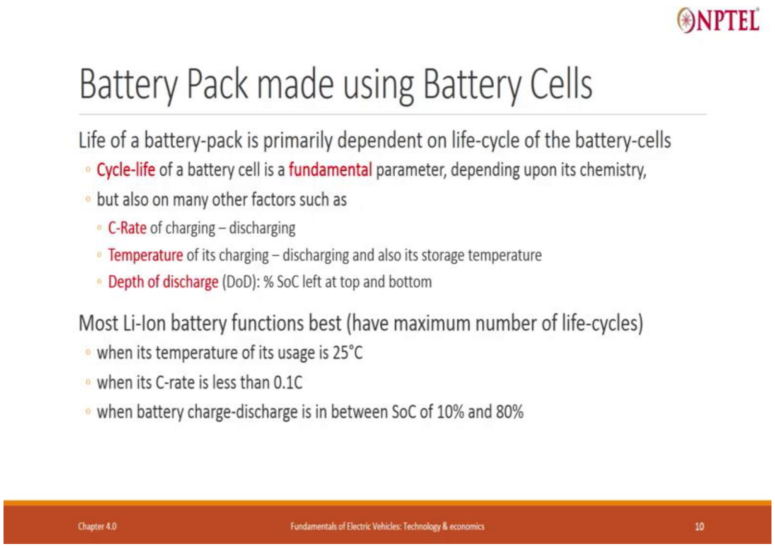

Then I had talked about that how battery pack is made using battery cells, I am revising what I have done in the last class, life of battery pack is primarily dependent on the life of cycle of a cell. So, if the cell and every cell matters, if there are 100 cells that will go to assemble a battery, if 1 cell goes lower the whole battery pack goes lower. So, it is the cycle life of battery cells a fundamental parameter depending on its chemistry and other factors and normally defined by the manufacturer.

But then I talked about that the it is not a absolute number, the life cycle of a cycle life of a cell depends on the rate at which it is charged and discharged, so C rate of charging. It depends on the temperature at which it is charged and discharged, I talked about the 25 degree centigrade is the best temperature for lithium ion batteries, you charge it higher the life cycle goes down, you charge it lower life goes down, so it will also depend on the C rate, depth of discharge, if you try to use 100 percent depth of discharge the battery life will significantly go down.

So, you tend to leave something at the top and the bottom that improve the life of the battery. So, most lithium ion battery performs best at 25 degree centigrade you will say at 0.1 C, but that is very low rate you will actually use it more higher rate to that extend the life cycles will go down. when the battery charge is between 10 percent to 80 percent it is only about 70 percent, that is the best. But now you have to reach a compromise, this will mean the battery actually will be used only a limited extend. So, lithium ion manufacturer may guarantee that a 1000 cycle if you charge at C by 2 rate at 25 degree centigrade at 85 percent DOD.

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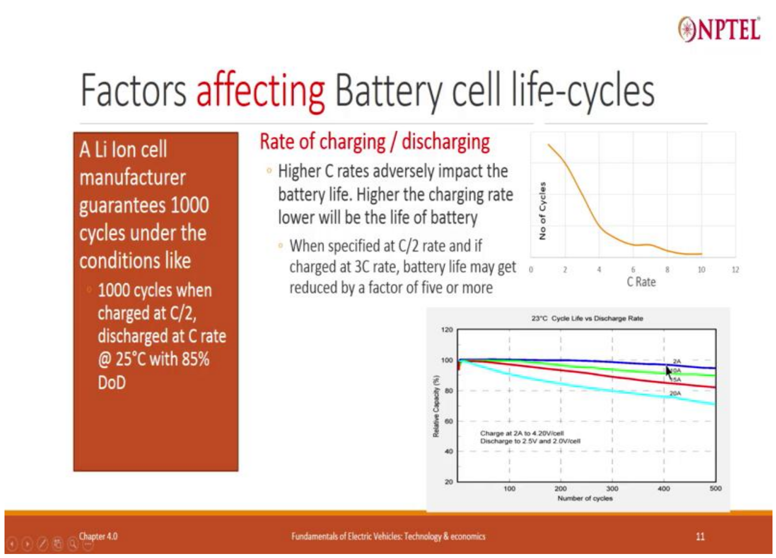

This is what a manufacturer may give it to you. And now you have to interpret no, no, no I do not want to, I would like to do 90 percent, so how much deterioration will take place? And if I want to go off from 25 degree centigrade how much deterioration will take place? So, as I told you one of the biggest problem is rate of charge discharge, if charging and discharging is done at higher rate it imparts a life of the battery. The life of the battery really goes like this.

So, at 0.5 C and 1 C it can give you a decent life, you start charging at 2 C, 3 C or discharging a 2 C, 3 C it hurts, the charging hurts more discharging once in a while you can go at higher rate, charging you like to do at that 0.5 C or lower, if I look at it here is a cell and a different 2A 10A 15A and 20A the life cycle very quickly goes down to 80 percent, it can do 400 cycles less than 400 Cycles at 20 ampere at 2A it probably can do 1000 1500 Cycles. So, this is something that I talked about.

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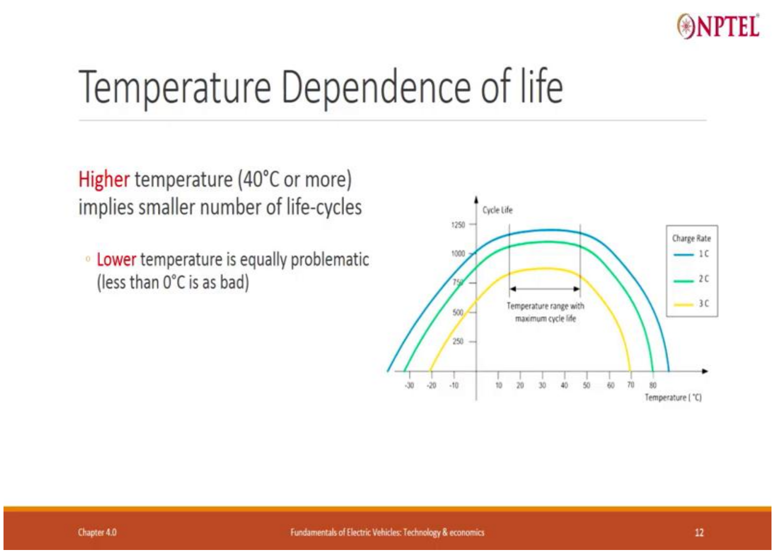

Then I sort of said that higher temperature impacts the life of the battery, lower temperature effects the life of the battery, a minus temperature does impact the life of the battery, you like it to operate probably between 15 degrees and 35 degree centigrade, again it will depend on battery to battery, you will buy from manufacturer 1, who may say this is the optimal place another one will say another optimal place is something else.

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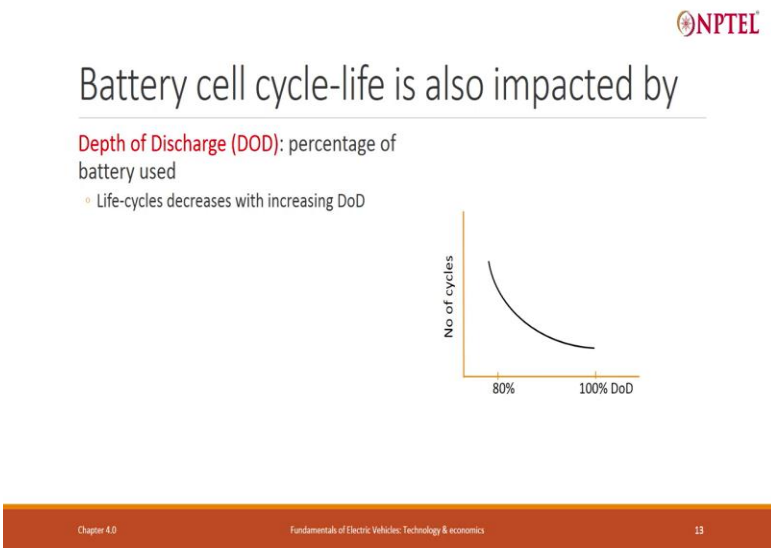

Depth of discharge, 100 percent gives you a very few little cycle, 80 percent give you good cycles, but 75 85 percent will also give you a decent cycle. So, typically 80 to 85 percent, there are good quality battery which you can have 90 percent depth of discharge still works all right. So, I talked about that we will leave the window at the top or at the bottom are talked about I am just repeating it or not.

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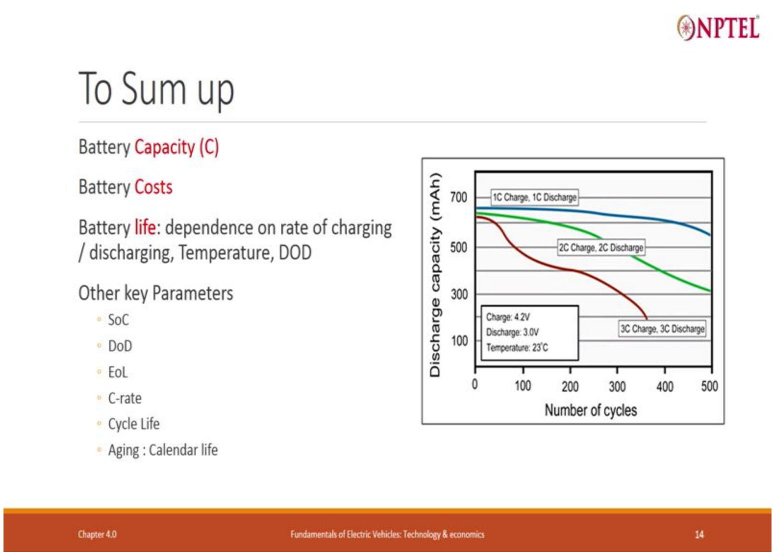

So, to sum up, we had talked about battery capacity and battery costs are the two important parameters, it will depend on the battery life because finally usage cost depends on the battery life and the battery life itself is dependent on the rate of charging discharging, temperature, depth of discharge. We also defined other parameter, like state of charge, depth of discharge, end of life, C rate, cycle life, aging, etcetera.

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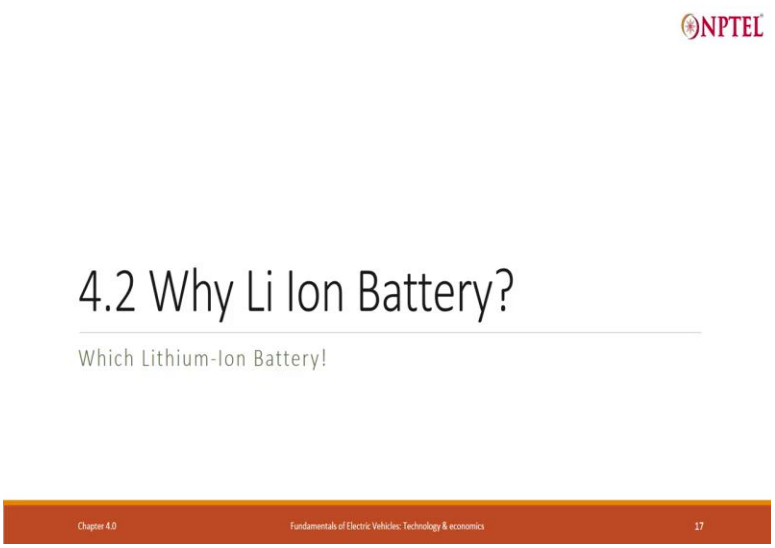

Have we had done that, now I will come to what I want you to teach today. Why do we prefer using lithium ion battery? Lithium ion battery has become more or less the battery of choice for all electric vehicles today. And what is the reason? So, let us look at the battery history.

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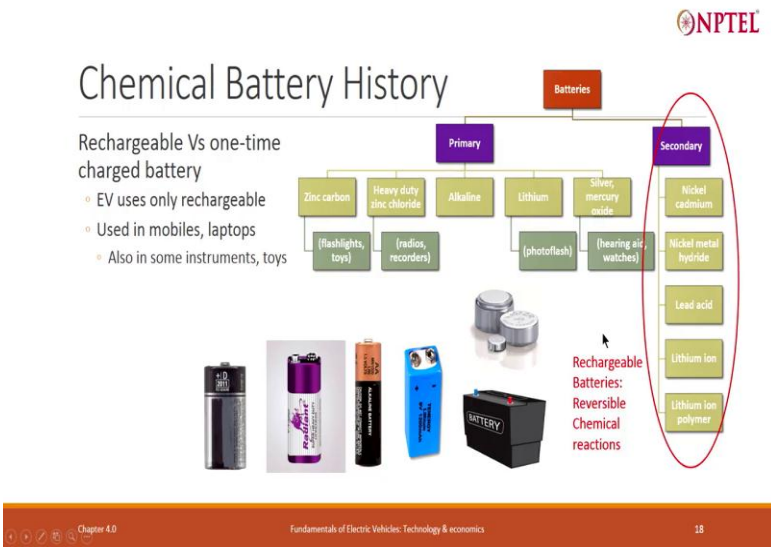

The first important thing is it a one-time charged battery, you buy a battery normally we buy for a torch or pencil cell or are slightly bigger cell, once it becomes bad you throw it away. That is a one-time charge, it is actually get comes to you charged from the factory and you cannot charge it again. As opposed to that there is it those kind of cells are no use to us in electric vehicles, we want a rechargeable, even in cell phone I want a rechargeable, one-time charge once are of no use. I do not want to change cells all the time, laptop also you want a rechargeable cells.

So, the rechargeable cells are called secondary cells, one-time charge are so the primary cells, the secondary sells itself is started with nickel cadmium, 25 years back we used to have in rechargeable, we used to have a camera in which you put a rechargeable battery, if there are other devices you put a rechargeable battery and that used to nickel-cadmium, it grew to nickel metal hydride, then lead-acid became very problem.

But very you useful, for example UPS in India most of them have lead acid batteries and then came lithium ion and we are starting to talk about other lithium-ion technology, lithium ion polymer, solid state lithium, ion battery, they are all variations of lithium ion batteries. Now, why did this come up? And what does it really mean? I also want to show you different kinds of battery, there is a battery pack like this, there are cells which are like a coin cells, there are different sizes and things like that.

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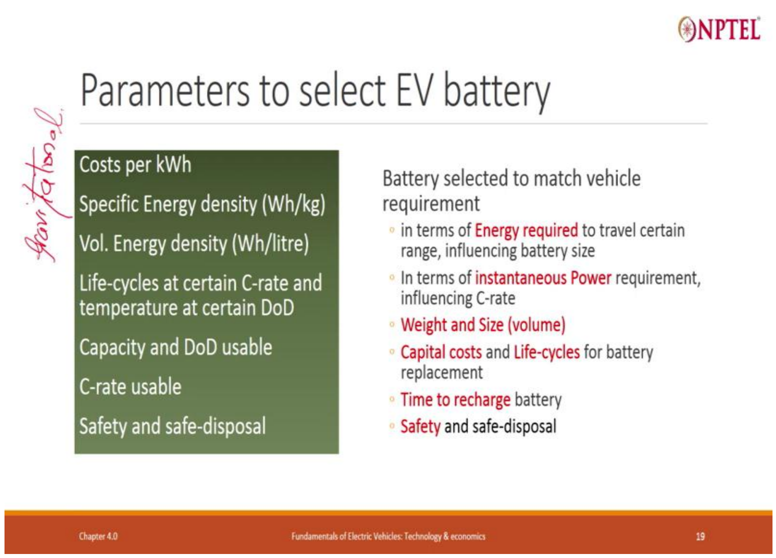

What determines, what do you save, what is the desirable specs for the battery? What are the things that you really like to look at? Of course, since we are talking a larger battery seem a very small battery did not matter as much the cost will be one of the most important factor if I want to buy a 20 kilowatt hour battery, how much will it cost, cost per kilowatt hour is a very important parameter.

And cost per kilowatt hour is very high at one time, it has gone down. There is a cell cost and there is a pack cost and the pack cost of course depends on the cell cost but pack cost is cell cost plus extra, we well get into it. What are the parameters that makes most difference is called specific energy density, sometimes also called gravitational energy density, it is defined in terms of Watt hour per kg, why? Because almost all the items which use rechargeable are something that you carry along, your cell phone, your laptop, even your camera.

So, since you carry it along question is after one charge you want to see that how long it lasts, so you want a slightly bigger cells. But the question is how much will it weigh? Will the weight in the cell phone battery become so large that I do not like it, cell phones beauty comes from its lightweight, you will say for a vehicle it matters, well it does.

Because it weigh, the cells size, the battery pack is very large 20 kilowatt, 30 kilowatt hour, so weight will become very large and if the weight of the vehicle increases its usage of power increases the lie the battery you will either have to put larger battery which will again increase the weight of the vehicle or it will go smaller range. So, weight makes a huge difference.

The second reason weight makes a difference, because the weight is a reflection of weight of the materials that you use in the battery. And as I talked to you earlier, the Lithium-ion battery is the primary pair material is lithium, manganese, cobalt, nickel and graphite, these are expensive materials, if you use half as much watt hour per kg doubles you will use half as much material as you would have used when it was not doubled for a same kilowatt-hour battery.

Now, half as much material uses almost will half the size, cost of battery. So, cost of the battery is very dependent on energy density. So, this is one of the most important parameter, driving the new research in the battery, you want the cost to come down and therefore you want higher energy density, volume energy density, how much what is the size, even if weight is one part the size becomes another, you do not want your cell phone to a too bulky.

Even for a two wheeler is thus size becomes too large, you cannot put it those space to put it in there. The third important parameter which had being talking right from the beginning is C rate, what is the number, sorry, life cycles are certainly C rate, at certain temperature, at certain depth of discharge, life cycle will mean not just the cost how long will this battery pack last, because after that you will have to replace it.

So, that becomes a important parameter, of course the capacity and depth of discharge usable becomes important C rate usable, safety and save disposals, so these are the parameters which defines electric vehicle. Battery of course is selected to match the vehicle requirement, you know vehicle requires 20 kilowatt hour for certain range, you to have to 20 kilowatt hour, so battery selected to match the vehicle requirement.

It has to match it in two ways, one it has to match in terms of instantaneous power, if battery certainly needs say 40 kilowatt, if you have a battery which is 10 kilowatt hour it means it will require 4 C and that is not good, you have to have a minimum size the battery to be a possibly 20 kilowatt. And it is a motor guys who will tell you what is the power required.

So, power required the instantaneous power required influences the C rate and the capacity of the battery and of course weight and size becomes a very important component as I talked about, capital cost becomes very important, life cycles becomes very important, because capital cost has to be divided by life cycle, number of years that I can use, that is one, second you want to take into account the interest rate we will come to that later on.

Because if you have borrowed money, it will mean that you are going to pay interest. A extremely important parameter is time to recharge the battery, I come I am have run out of battery, I go connect it to the charger, can I recharge in 10 minutes, can you charge in 5 minutes that would be ideal, I normally fill petrol in 5 minutes, I can charge in 10 minutes, well I may willing to wait, what if I cannot charge in less than 1 hour? That becomes though, either I have to wait it for 1 hour or there is a very interesting you knew go forward and you will see a Japanese standard for a charger is called CHAdeMO, CHAdeMO, CHAdeMO is standard for the charger battery.

Actually, if you look at the word you see well I put it on charger let us go to have a cup of tea and come back, CHA comes from the Japanese word CHA and Indian word chai may have be the same, deMO basically lets go for and have a cup of tea or even more, but it will take 2 hour to charge then, even tea you cannot go, can I do partial charge all those issues will come. Does it take 4 hours to charge?

Remember charging in 1 hour is 1 C and I had said not the best for the battery, 0.5 C or 0.3 C would have been good for the battery, which means 3 hours charge or even 4 hours charge you have been got from the battery. But maybe you have to charge it sometime in 1 C, sometimes you have to charge faster than 1 C, 2C which means in half an hour, the questions that you will act, can the battery withstand that, what will happen to the life cycle of the battery and then of course you have to charge at higher, charge rate. So, these are the questions, we will get into depth of these things.

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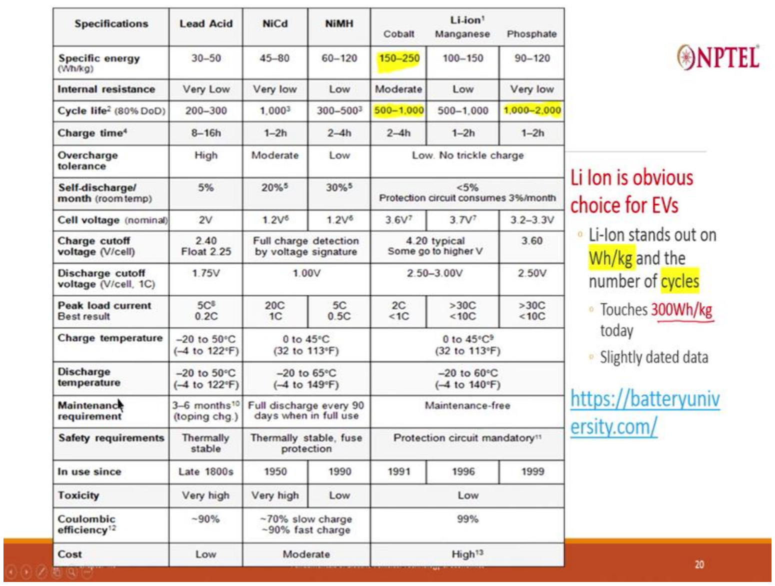

Specifications	Lead Acid	NiCd	NiMH	Li-ion[1] Cobalt	Li-ion[1] Manganese	Li-ion[1] Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low
Cycle life[2] (80% DoD)	200–300	1,000[3]	300–500[3]	500–1,000	500–1,000	1,000–2,000
Charge time[4]	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/ month (room temp)	5%	20%[5]	30%[5]	<5% Protection circuit consumes 3%/month		
Cell voltage (nominal)	2V	1.2V[6]	1.2V[6]	3.6V[7]	3.7V[7]	3.2–3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75V	1.00V		2.50–3.00V		2.50V
Peak load current Best result	5C[8] 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C (–4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C[9] (32 to 113°F)		
Discharge temperature	–20 to 50°C (–4 to 122°F)	–20 to 65°C (–4 to 149°F)		–20 to 60°C (–4 to 140°F)		
Maintenance requirement	3–6 months[10] (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory[11]		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency[12]	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High[13]		

Let us, look at the batteries that I talked about, the historical battery. If I look at it, they will, there was a lead acid battery, still commonly used, nickel cadmium almost gone, metal hydride it used to be the their in your calculator for example, used to use this batteries a lot, rechargeable batteries.

Student: Camera.

Professor: Camera used to use. And then there are Lithium-ion batteries and lithium-ion also there are three kinds that I am saying there is a phosphate batteries, there is a we will get into more detail, there is a Cobalt batteries and manganese batteries. Look at the first parameter here watt hour per kg, it has been evolving and whereas it is only 30 to 40 50 watt hour per kg, which means not only it will be heavy, but also it will use lot of materials.

Nickel cadmium went a little better, nickel metal hydride did a little better, then came all this phosphate, magnesium and now Cobalt, 250 watt hour per kg, actually this is old data we have now crossed 300 watt hour per kg, 300 so this is what I am saying, we have crossed 300 watt hour per kg, extremely important, what will happen? Now, my weight of the battery reduces, if I use instead of 300 if I use 30 my battery weight would have become 10 times.

So, we want to use 250, 300, these are by the way for the cells, not for the whole pack, pack maybe have some extra weight and we will figure out how much. So, it also means at 300 watt hour per kg the cost comes down, if I use for example lithium phosphate suppose it is a 100 and this is now 300 my cost will be approximately one third.

And that is the reason we used to have 1000 dollar per kilowatt hour and it is gone down to almost 100 dollars per kilo watt hour, this has happened primarily the most important parameter specific energy also called gravitational energy and it is this which will drive the future battles also we will come to that, internal resistance, we want that to be low, because otherwise that much heat will get dissipated, cycle life, we want the cycle life to be close to 2000, at least 1000 2000.

So, this is not entirely correct the Cobalt NMC battery today will give you close to 2000 cycles and even 5000 cycles, there are that battery which gives you 5000 cycles. Charge time ideal is 1 to 2 hour, 2 hour, 1 hour occasionally, they impact the life of battery, there are of course other things overcharge tolerance, self-discharge, self-discharge for lithium ion battery is low 5 percent, 2 to 3 percent per month, means you have left the battery on charging, charged battery, end of the month it may be 97 percent or 95 percent, not too bad.

Of course, you can charge it, cell voltage, charge cut off all these plays important role, temperature minus 22 plus 60 degree centigrade, charging temperature 0 to 45, this play important role, maintenance-free of course we have only talked about maintenance-free battery, earlier batteries did have maintenance and the other dominant batteries that are used now. Toxicity of lithium ion battery is low compared to the earlier ones, but even then you have should recycle because material cost is high, if you recycle you get back the material. So, well cost is considered high, but it is actually falling down very rapidly

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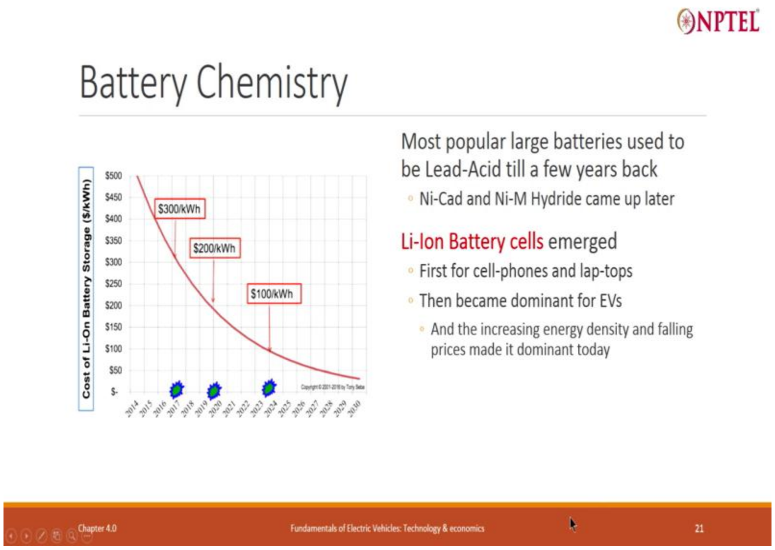

Battery Chemistry. Most popular battery chemistry, this one I was pointing out, it is to be closed to 1000, this is 500 dollars, it was even higher, in 2010 it was 1000 dollars per kilowatt hour and if you see this is going down it has come down to a 100 dollars per kilowatt hour, its already reach 100 dollars per kilowatt hour at cell level. Lead acid battery on the other hand is reasonably expensive, well it is not as expensive as in terms of actually cost it is less, but the number of cycles that it gives is little, so it ends up being very expensive. So, lithium ion battery cells emerge somewhere here and since then it has become the dominant thing for cell phone, laptops and the cost has been coming down as the energy density keeps on going up.

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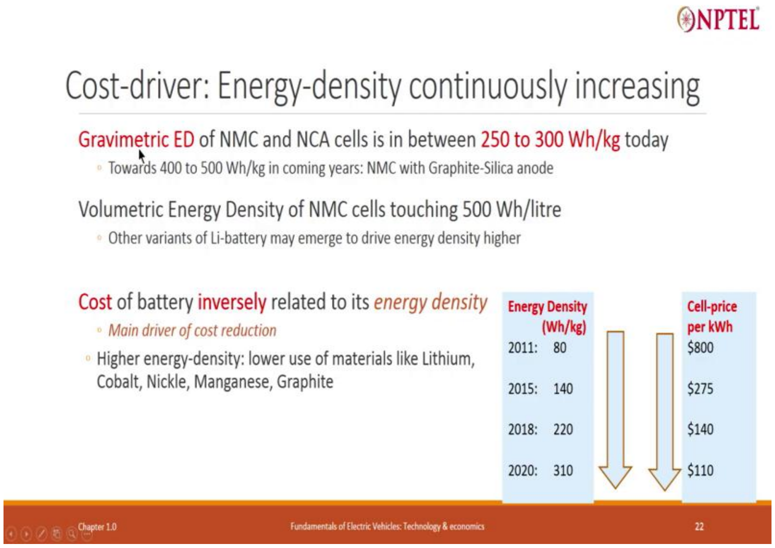

This is again telling you the same thing, look at from 2011 we started with 80 watt hour per kg we have gone to 300, see the cost from 800 dollars has come to a 110 dollars. So, today we have 250 to 300 watt hour per kg, now there are promises that if I take NMC battery, but if I put graphite and silica anode in a few years, I may get to 400 watt hour per kg, 500 watt hour per kg.

Volumetric energy density is already touching 500 watt hour per litre, remember these are for the cells, for the pack it depends on people like Doctor Kaushal, they are people who make it such that the pack is only 20 percent more than cells, 25 percent more than cells, the others who will make it two times the cell weight or volume then becomes a big problem. So, as I point out cost of battery is inversely proportional to energy density and it is the main driver for cost reduction, a high energy density batteries today use lithium, cobalt, nickel,1 manganese and graphite all of them are expensive material.