Fundamentals of Electric Vehicles: Technology and Economics
Professor Ashok Jhunjhunwala
Indian Institute of Technology Madras
Technology and Economics
Lecture 1
Electric Vehicles Outlines

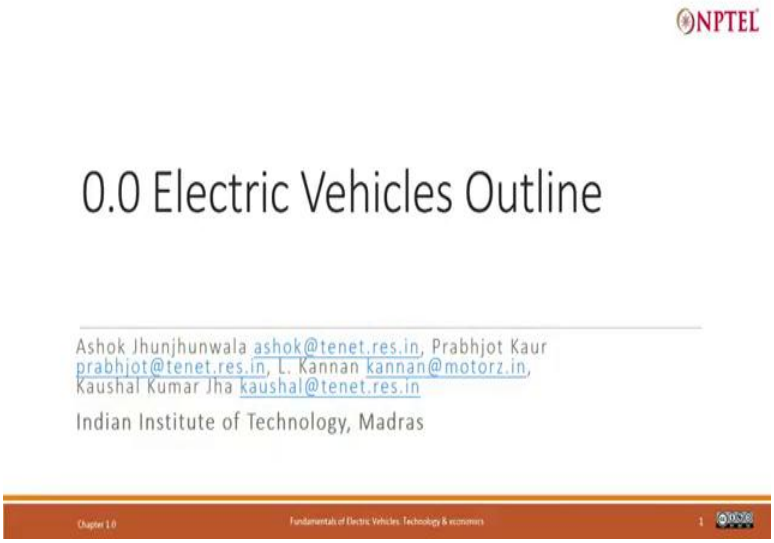
This is a course on Electric Vehicles. We are going to look at both the technology as well as economics from Indian point of view in this course. It is a fairly comprehensive course but the course is still designed for not just electrical engineers, electronics and communication engineers but also for computer science people, for mechanical engineers, for engineering mechanics people, people with even civil engineering and aeronautical engineering.

And therefore a course will basically assume that you have some fundamentals of engineering. Beyond that we will completely build it because anyway electric vehicle is a combination of mechanical electrical field. So we are going to actually offer this course as a comprehensive course which any of these discipline people can take.

And as I pointed out while the course is primarily on technology, there is a sufficient amount of material on economics. And we will talk about cost, prices and what does, how does that impact overall acceptance of electric vehicles. And we will be always talking in rupees term, we will not use the dollar term if you want to use the dollar well proximately 75 rupees is a dollar but we will be using mostly rupee term.

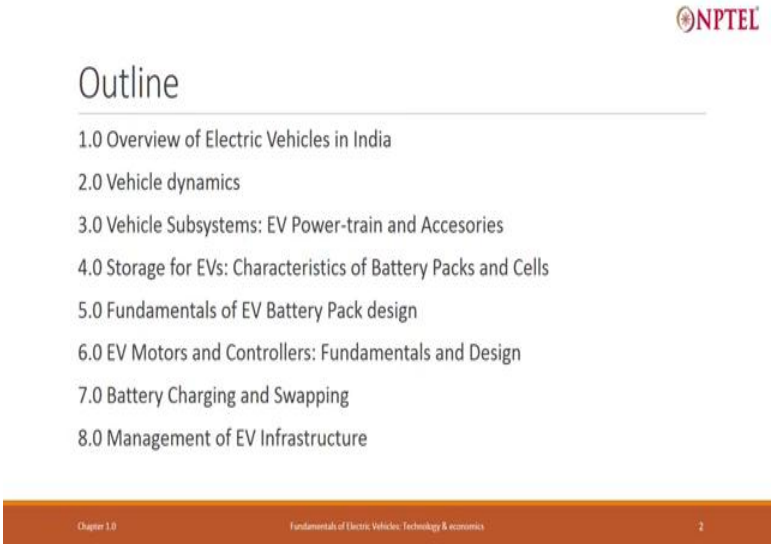
Once in a while we may use dollar, dollar is 75 rupees. The course is going to be joint, it is a course which is going to be about 27-28 hours plus some assignments and things like that, it will have rigorous, it will have plenty of assignments. And it will be taught by 4 of us not just me.

(Refer Slide Time: 02:21)



I am Professor Jhunjhunwala from IIT, Madras. And along with me in this course we will have Doctor Prabhjot Kaur and Doctor Kaushal Jha and our professor of practice L Kannan. So 4 of us are going to cover different aspect most of it is going to be covered by me and parts of it is going to be covered by the others.

(Refer Slide Time: 02:50)



So if I look at the course outline per say, this is the course outline. We will start with an overview of electric vehicles and this overview is not going to be very short overview it is going

to be a somewhat comprehensive overview because we will look at from India point of view what is going on, what are the keys issues, what are the key concerns.

The focus is India, the second co-part of this is on vehicle dynamics. And the vehicle dynamics in some sense is actually valid for electric vehicle as well as internal combustion engine vehicle, any petrol vehicle, diesel vehicle. So it is equally valid. We are going to very quickly cover that, normally it is taught by mechanical engineering, automotive engineering and all that we will cover that because that is important component based on which the whole electric vehicles are built.

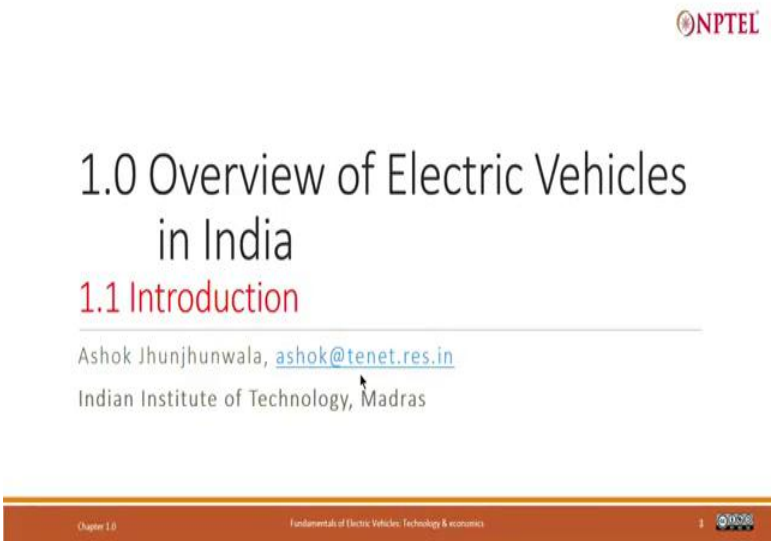
We are then going to look the vehicles sub-systems, EV sub-systems. What is a EV power train? What it an accessories? After that we are going to get into storage. The EV storage, the battery. How do you do the battery pack design? What are the key considerations? First we look at how do you really make from cells to packs and what are the key considerations?

And later on we are going to look at the actual design of a battery. We will look at the thermal aspect, we will look at the mechanical aspect, we will get into what is something called battery management system, BMS has to do. How do you do the electrical design, what are the pitfalls that you have in doing such designs and we will get into that.

Then we are going to get into details of electric vehicles, motors and controllers. Motors and controllers will play a very important role and we will get into, specifically, what we call a permanent heat magnet synchronous motor we will get into details of that. We will give you a very good overview. Then will look at battery charging and swapping, infrastructure, what is charge, chargers, right form beginning we will be talking about charging and swapping and we will get into details of that in battery charging and swapping.

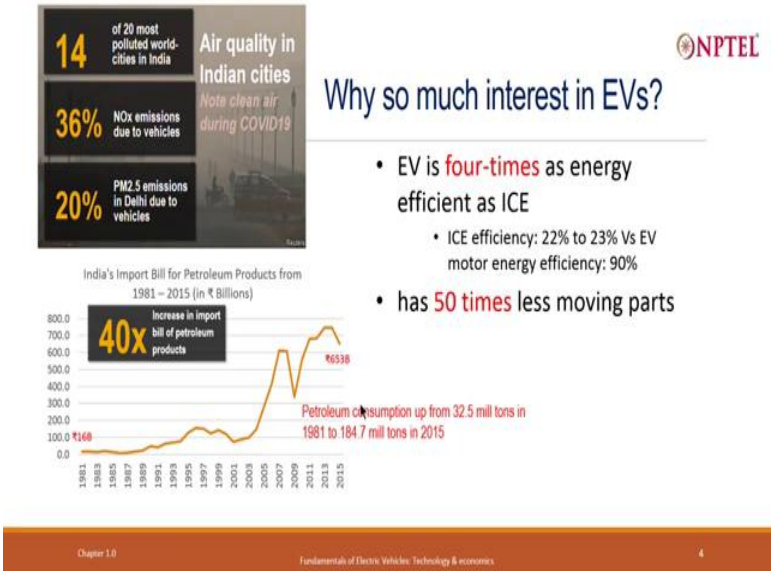
And finally we are going to get into the management of electric vehicle ecosystem, the whole infrastructure. The managing of that carrying out analytics of that actually helps in electric vehicle proliferation. So we are going to get into that. This is what we are going to do, the primary we will of course give you the full notes, the lecture notes, will give you the assignments and things like that. I will give you a few references but primarily the course is going to be taught in a very different manner things have been actually learnt and picked up. And we are going to try to cover this in details.

(Refer Slide Time: 06:11)



So with that I am going to start with Overview of Electric Vehicles. The overview of electric vehicles in India and I, the introduction I am going to start with and tell you some very simple thing.

(Refer Slide Time: 06:25)



First of all, a question is why is there so much interest in EV in India? A very simple thing that India has 14 of the 20 most polluted cities in the world. And while there may be other sources of pollution. In this Covid times those of you have stepped out or seen and felt a clean air after

years. So basically the electric vehicles, the petrol vehicles stopped plying, the diesel vehicles were not there and suddenly you see the cleanliness of the air.

So the electric (vehicles), the vehicles, the petrol and diesel vehicles do contribute very significantly to the poor air quality and that is part of the reason why everybody saw saying can we get electric vehicles, can we replace that, can we at least eliminate this source of pollution? The second thing is of course what does the internal combustion engine vehicle, the petrol vehicle and diesel vehicle do?

It requires petrol and diesel and we just keep on importing the petrol and diesel. We have actually very little probably not more than 10 percent of what we use is produced in India. The rest of it just continues to push up our purchases and therefore a foreign exchange out go. It continuously does that and in fact is a prime reason for our rupee to be weak as compare to the currency around the world.

We have very-very large import and we of course want to get rid of that. Once we move to electric vehicle, electricity can be produced in India we will talk about it and plenty. And we will suddenly get rid of this. So this is a very important motivation. The other motivation is purely in energy efficiency terms this actually came to me also a surprise that the electric vehicle is 4 times more energy efficient as compared to a petrol engine or a diesel engine or internal combustion engine.

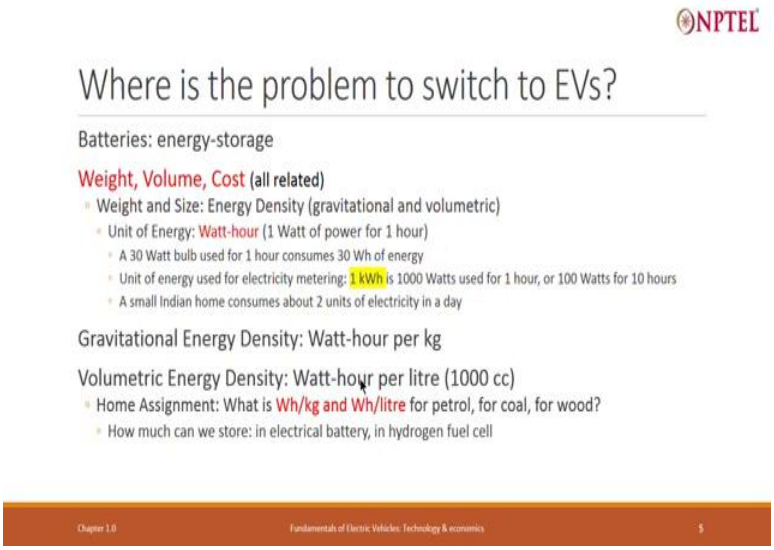
This is something that internal combustion engine basically has 22, 23, 24 percent efficiency. Whereas motors and controllers we are starting with about 90 percent efficiency. So it is basically 4 times less energy it consumes, 4 times higher energy efficiency. And this is something the world is moving towards higher and higher energy efficiency not consumable energy and waste because consuming energy and wasting it is not just impacting the environment nearby but it is actually also impacting the whole earth.

So very important reason we want to move out it is actually higher efficiency and everything in the world is moving towards higher efficiency. So whether we like it or not internal combustion engine with petrol and diesel will die. How long it takes one can argue and electric vehicles will actually emerge. It also has another important component. Actually the, a ice vehicle, a vehicle which is petrol and diesel vehicle has very large number of moving parts.

Whereas once you come to electric vehicle it has actually has very few moving parts and therefore almost 50 times less number of moving parts and therefore much more reliable. So essentially this implies that basically the vehicle can last much longer and we do not have to keep on replacing it as often.

So from a environment point of view, from the point of if higher efficiency, point of view of not requiring replacement in every terms electric vehicles scores out far above anything else. Where is the problem? Why are we not doing that? Why did we did not do yesterday and why cannot we do it faster?

(Refer Slide Time: 11:16)



The problem to switch to EV is the battery. In a petrol vehicle what do you have? You have a petrol tank and you fill up petrol or you fill up diesel or what is somewhere else called gas. There is a gas tank. In electric vehicles the container for energy is a battery and this battery is where you charge, you store energy electrical energy. So a petrol tank will be replaced by a battery. Now there is a problem with electric battery. It is far more higher weight as compared to a tank, even a fuel tank. In has far higher volume and we will look into it and far higher cost.

In every, in all the 3 dimension battery scores far worse than a petrol tank filled with petrol or diesel and we will look into where are we and we will see what can be done and how things have been progressing. In fact, this if we can figure out electric battery and figure out how to actually get going with that the problem of EV becomes simple.

So we are going to look into this in great detail as we go on. But we will look at weight, volume and cost all 3 things. For example, weight and size; weight and size is often refer to as energy density. Energy density either in gravitational form which is weight or energy density in volumetric form which is the size.

And the unit of energy of course all of us use or most of people know is, is Watt-hour. Watt is the unit of power, 1 Watt use for 1 hour is Watt-hour, Watt hour is a unit of energy and that is what we are going to look and we are going to look at how much energy density in terms of Watt-hour. Now just to give you up understanding a 30-watt bulb that we often use at our home if we keep lighted for 1 hour it consumes about 30 watt hour.

The unit of energy that we are most familiar with, the common energy it is called 1 unit of electricity. What is 1 unit of electricity? Is actually 1 kilo watt hour, so it is equivalent to almost 33 bulbs of 30 watts burning for 1 hour. It is 1000 watt hours and 1 kilo watt hour and this 1 kilo watt hour of electricity at our home for example cost us about 5 rupees, in a commercial complex cost higher; 8 rupees, 9 rupees, 10 rupees.

At home it costs us about 5 rupees and basically it is either 1000 watts for 1 hour or 100 watts for 10 hours. You can, so this is you take the power and you multiply it by the time for at which the power is used and that gives you watt hour. For example, a small Indian home not a very large but a small, 1 bedroom home very-very small. It is consumes about 2 units of electricity a day. And at 5 rupees it will mean 10 rupees, so monthly bill will be 300 rupees.

So small homes; 1 bedroom, 2 bedroom typically spends that much money. It consumes 2 units of electricity a day. Of course larger homes consumes far more. So we must have that feel of what we are talking about. The weight is dependent on what is called gravitational energy density and gravitational energy density is given in watt hour per kg.

So for, if I have a battery which is 20 kg how many watt hour will it give me? So the energy density of the battery will be given in terms of watt hour per kg. And throughout the course this is one term watt hour per kilogram is going to play a very-very important role and we will keep on talking about it. Because we have to put a battery container, we have to put a battery the electricity the energy container in a vehicle and what will it weigh?

That is going to be a very important consideration. And therefore the gravitational energy density is in terms of watt hour per kg. A very similar term is in terms of volumetric energy density and this is watt hour per liter, the term use is watt hour per liter, liter 1000 cc. What is a volume? If I put a 10 kilo watt hour a battery how much will it weigh? How much will volume will it occupy?

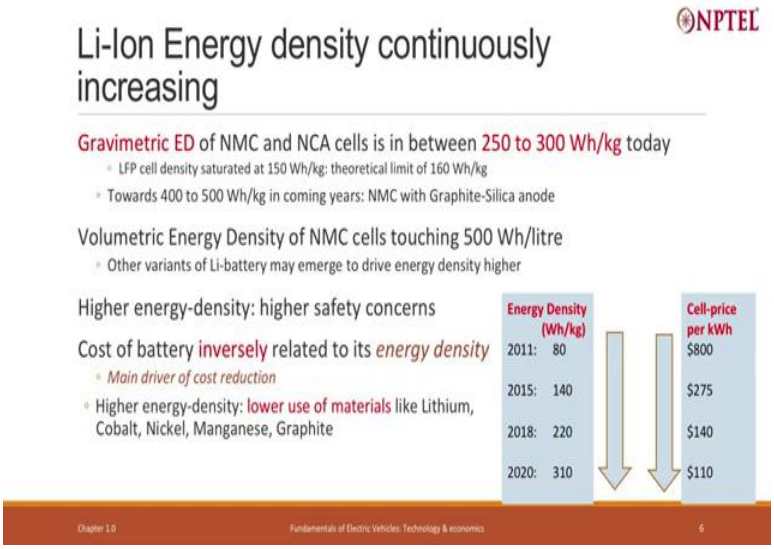
We will look into details of this. I actually want to start by giving you a home assignment, an assignments will be given periodically and you had actually have to submit this home assignment on the portal, they will be corrected and will be graded based of that. The first home assignment that I am giving you is a very simple thing.

Can you take three other known sources of energy; petrol, coal and may be wood. So I go to the internet and search what is the watt hour per kg, you will actually be given some other units but does not matter convert it to watt hour per kg, they are simple energy converters you can use and convert this to watt hour per kg. What we want a simple answer.

(()) (18:14) a petrol, 1 kg of petrol, how many watt hour? Equivalent energy of watt hour does it do? So watt hour per kg for petrol, coal and wood and similarly we want you to find out watt hour per liter for petrol, coal and wood. You have to search internet to get this data and you will have to answer this as a part of the first assignment.

So essentially we want to look at how much energy can we store in electrical battery, in hydrogen fuel cell, we will not talk much about hydrogen fuel cell but that is another potential future energy container. So these are all to be compared. Petrol, diesel, wood, electrical energy and fuel cell and everywhere we will have to look at the watt hour per kg and watt hour per liter.

(Refer Slide Time: 19:30)



So just let me start by sort of saying, the battery that we commonly used in electric vehicle today is a lithium-ion battery. And you know the reason why we use that is two things are happening over last 10 years ever since electric vehicles have become popular. The energy density of the lithium-ion battery gravitational energy density has been continuously increasing.

Take the numbers that were there in 2011, energy density of a lithium-ion battery was only 80 watt hour per kg. Today it is around 300, 310 watt hour per (energy) kg. And is expected that this will continue to increase as go on. Can we get to 500 watt hour per kg? In what time frame? Can we get to 1000 watt hour per kg? This is a question that is asked as the batteries evolve we will see that.

Look at the other important thing, as the watt hour per kg improves the price per kilo watt hour keeps on falling, this is a cell price, this is not a battery price but the cell price per kilo watt hour was 800 dollars when it was 80 watt hour per kg and is now down to 100 dollars per kilo watt hour when the energy density is 300.

Why does this happen? Now of course we have learnt to do make better battery and things like that all that plays in the volume plays a important role but the most important role is played by how much kg of raw materials that we used. So for a kilo watt hour as the energy density improves for example if it was 80 watt hour per kg we use 12 kilo grams of material.

What that material is we will get into that, as we went into 300 watt hour per kg we are approximately using 3 kilo gram of material, so the material itself from about 12 kg we have got it down to 3 kg. Simply because watt hour per kilogram of the battery has improved. So if you are going to bring down the material used by almost 4 times the cost will automatically fall down by 4 times. Because the material dominates the cost.

There are other costs that does not necessarily fall as rapidly but that has also fallen and today we are looking at 100 to 110 dollars of battery at close to 300 watt hour per kg. Will the watt hour per kg further improves to 500, this is expected to fall even more, may be 70, may be 65 dollar per kilo watt hour.

And we will see therefore the cost part of it will no longer be a serious issue. Of course as watt hour per kg improves, it improves your weight that you require to get 1 kilo watt hour or 50 kilo watt hour will also go down, so weight will go down. And actually volume is also very related. So as the energy density improves you will see the battery size going down for the same range, battery weight going down and battery cost falling.

So this is the very important thing that is going on. Now the battery that I used that we will get into details of this, today the batteries that are used are also called NMC or NCA these are two most commonly used nickel, manganese and cobalt is the use of these batteries or NCA nickel, cobalt and aluminium.

A few years back a battery that was very popular was LFP lithium ferrous phosphate and it was China actually led that and did a lot of work on LFP and made lot of LFP battery possible. And we were also importing it from China. The LFP battery on the other hand actually cannot go above 150 to 160 watt hour per kilogram.

So essentially it is a battery whose life has ended R and D is not going to give you much more than that. So within China it is being used less and less and sooner we discard it better it is. The current battery is NMC and we keep watching for new battery we will talk about these things later in great detail.

Today we are looking at 400 to 500 watt hour per kg and there are two primarily thing, it will be NMC battery or NCA battery. It may have a graphite silica anode, we will talk about it as we go

on. The volumetric energy density today the common is 500 watt hour per liter. This as the watt hour per kg improves volumetric energy density also improves. So this is what we look at.

Now what are we trying to do? We are trying to improve the watt hour per kg which means more and more energy we are packing into smaller and smaller area. If you pack a lot of energy into smaller and smaller area what does it mean? If anything goes wrong it can burst, it can become a bomb. So on the one hand we are improving watt hour per kg we are increasing it, at the same time the basically we are making things more unsafe.

That is a natural thing, so we have to deal with it. We have to stop using higher energy density you will see for example petrol has far more higher energy density. We have learnt to use petrol. At one time probably say a 80 years back, 100 years back it was considered unsafe. Today petrol is not considered unsafe. So just imagine put a small matchstick and the whole thing lights up. We have learnt how to handle.

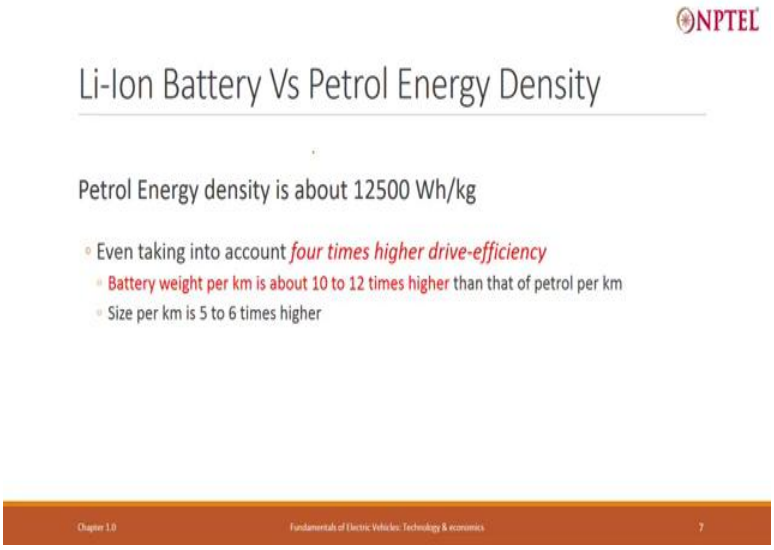
A small spark can light up the petrol. Actually petrol is far more risky than these batteries that we are talking about. We have learnt to deal with it and we have learnt to deal with high energy density. Because that is the only thing that will make the cost go down, weight goes down, volume goes down for a battery, okay.

Cost as I said told you is inversely related to energy density. So as energy density improves the cost goes down. The materials that are being used commonly is lithium, cobalt, nickel, manganese and graphite. We will get into details of this right now just try to remember, it is good practice to actually get the same information multiple times in a course first time you just kind of listen to it later on you start comprehending it and then you start remembering it.

So I think that is the approach that we will use while we are teaching the course. So just for example I was telling you how much is the petrol energy density? And if you look at the website and start searching for it you will find it is 12500 watt hour per kg. So on the one hand we are talking about 300 watt hour per kg another is 12500, it is 40 times, petrol is so much lighter. In the tank is not heavy and that is the advantage that a petrol vehicle has.

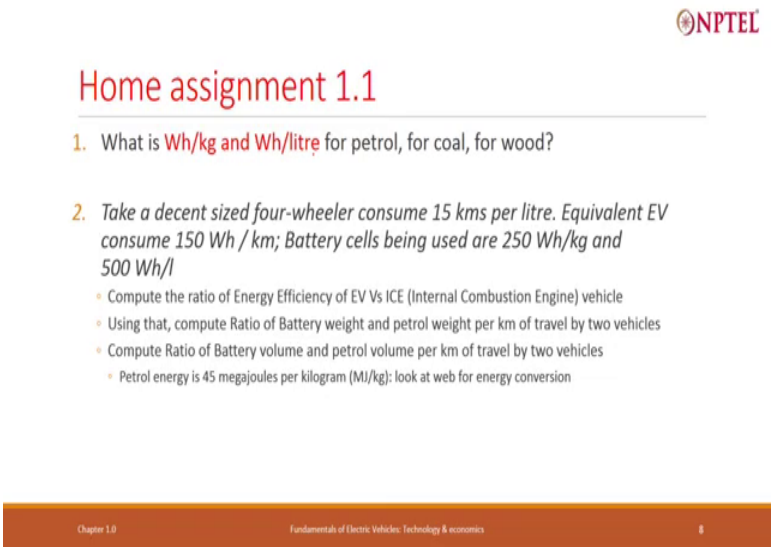
It can put lot of energy in the vehicle quite easily. Now remember that we have 4 times higher energy efficiency which means that actually we require 4 times less material in electric vehicle but even instead of 40 times it will become 10 times.

(Refer Slide Time: 29:24)



And this is something so battery weight is about 10 to 12 times higher than petrol for every kilometer that you travel and the current, current energy density. And size is about 5 to 6 times higher.

(Refer Slide Time: 29:50)



In fact, we will give you home assignment, this is the part of the home assignment. The first question is same what is watt hour per kg and watt hour for per liter for petrol, for coal and for wood? This is something as I told you, you search on the web, figure out the answer and provide the answer. There is a template to answer your home assignment, you have to go and enter that.

Remember that these corrections will be done automatically by computer, so you have to actually enter the numbers in the right boxes. But the question 2 is take a decent sized 4-wheeler, a car and let us assume that consumes 15 kilometers per liter. In an equivalent electric vehicle, it is a decent size not very small car, consume let us say 150 watt hour per kilometer.

Now 15 kilometers per liter many of you had heard of it (anybody) about the car today. 150 watt hour per kilometer in fact we will show you why it consumes 150 watt hour per kilometer as we go on in the course. Should it consume more or less we will talk about it and let us assume battery cells being used are 250 watt hour per kg, this is what is commonly available and we are using it and 500 watt hour per liter.

Compute the ratio of energy efficiency of electric vehicles versus ice. I have given you how much does, so purely in energy terms, how much does electric vehicle consume per kilometer? How much does a petrol vehicle consume per kilometer? And then compare and you will see the numbers with the numbers given you will see it is coming close to 4. Using that compute ratio of battery weight and petrol tank weight, weight per kilometer, petrol tank just not petrol, petrol tank weight per kilometer of travel for the 2 vehicles. One is electric vehicles, another is petrol vehicle. Then compute the ratio of the battery volume per kilometer for petrol and for electric vehicle.

You will require of course information, there is one information that you will require, how much is the petrol energy and it is there on the web you can search for it but basically use 45 mega joules per kilogram. This is and do the right conversion, look at the web for energy conversion. So these are the two problems that I expect you to do, you have actually learnt enough to be able to solve these problems largely from the web and do a little bit, we will give you a feel of what are the true energies that we are talking.