TU Delft

Electric Cars: Technology

DelftX eCARS2x

Content

1 Electric vehicles fundamentals

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1.1 Electric motor vs combustion engine

Most people generally do not understand the basics when it comes to comparing conventional cars with electric cars. In essence there are two fundamental characteristics that all cars have that you have to understand. If you do, everything all falls into place and the rest is details.

The first fundamental characteristic is energy storage. The second fundamental characteristic is the motor. Let's start with the motor that converts potential energy into kinetic energy.

You might think that there are many types of motors, but actually there are only two types when you look at the fundamentals. This has been true since the beginning of human history. So pay attention because this is going to be information that you can use forever. The first motor is the heat engine, and the second is the electric engine. Electric vehicles with the two types of motors are shown in Figure 1.1.

In a heat engine, burning releases the potential chemical energy in the fuel. The heat this produces causes expansion and this, in turn, drives some rotary motion. This is true for steam engines, sterling engines, diesel engines and gasoline engines.

Figure 1.2 shows how a four-stroke engine works. This is basically the modern gasoline engine and it was invented 150 years ago. On the first stroke, gasoline is injected into a chamber by opening a valve that is then closed again. On the second stroke, the cylinder moves upwards and the gasoline is compressed. On the third stroke, the energy in the fuel is harvested by igniting it. The resulting explosion drives the cylinder down and that produces a rotating motion. This is comparable to a bicycle, where pushing down the pedal moves the bicycle forwards. On the fourth and final stroke, the energy burned is emitted. It is all very ingenious but a heat engine has numerous problems.

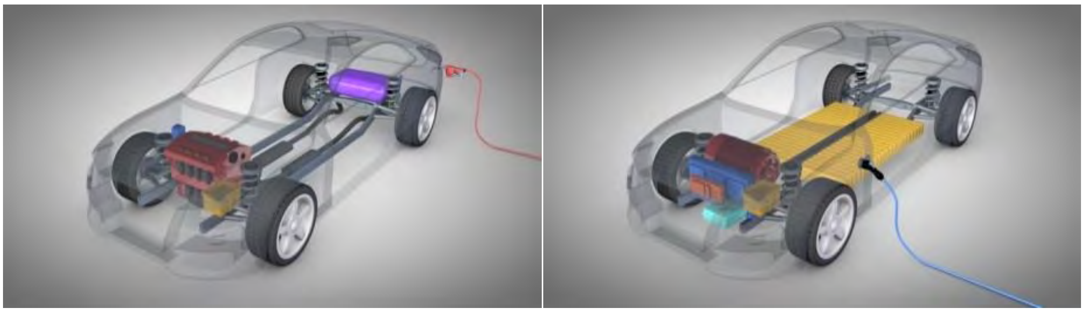


Figure 1.1 Internal combustion engine car (on the left) and electric car (on the right)

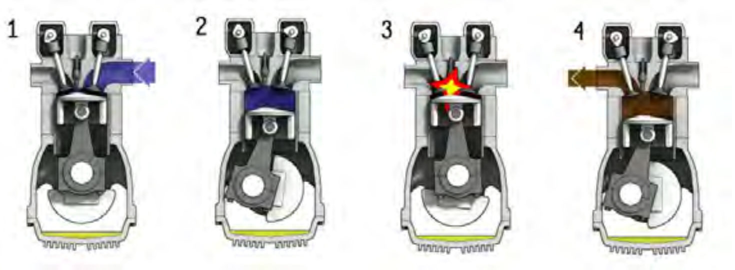


Figure 1.2 Four-stroke internal combustion engine sequence

The entire engine requires hundreds of precisely crafted moving parts. That makes the engine heavy and expensive. Since all the heat and explosions cause a lot of wear and tear, you need a lot of maintenance, and even then it wears down pretty quickly. The heat engine also wastes a lot of energy. In theory, we could improve the efficiency to about 50%, but that would mean a couple of things. Firstly the engine would become more expensive. Secondly it would have to run at an almost constant number of explosions, which is very hard to do in the real world. Finally the motor should be run at almost maximum power. In practice, even though we've been improving the internal combustion engine for more than 150 years now, a regular car wastes more than 75% of the energy it consumes as heat. And a sports car like the Bugatti Veyron wastes more than 95% of energy if you drive it in regular city traffic. For health and climate change, the biggest problem is the exhaust fumes. These fumes are unhealthy but the biggest problem is that burning 1 liter of gasoline produces 2.3 kilogram of carbon dioxide gas.

In an electric motor, it all works completely different. We will dive into all the types of electric engines later, but fundamentally they all work by using magnetic fields. You might still remember from school that magnets have poles. We say they have a north pole and a south pole, just like earth. If you put two magnets together you will see that opposites attract, as depicted in Figure 1.3.

If we take a coil of wire and make electricity flow through it, it creates it is own magnetic field. It has become a magnet. If we place this magnetic coil between two magnets, one side of the coil will be pushed up and the other side will be pushed down. This makes the coil turn until it is vertical. At that moment we quickly change the polarity. The effect is rotary motion and what you are seeing here is a simplified direct current motor in action.

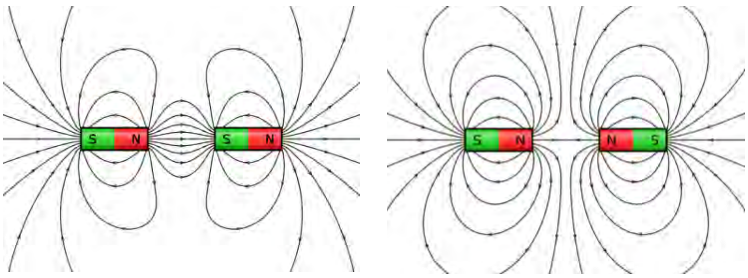


Figure 1.3 The magnetic field rejects and attracts based on polarity

Table 1.1 Heat engine vs electric motor overview

Internal combustion	Electric motor	Electric motor is...
1-3 kW/kg	3-10 kW/kg	3x more powerful
0.4 kW/L	13.6 kW/L	40x smaller
5-30 % efficient	93-96 % efficient	3-20x more efficient
Many moving parts	One moving part	Maintenance free

The advantages of the electric motor are numerous. It only has one moving part, we call that the rotor. Therefore, it can be relatively light, compact and inexpensive. And since magnetic fields are very *gentle*, an electric motor can last essentially forever without any maintenance. The energy efficiency of the motor can be close to 100% and you can win back energy when braking. Because of this, the average electric car is four times more efficient than the average conventional car. And if you compare sports cars the electric car is up to twenty times more efficient. So oversizing an electric engine does not materially reduce efficiency and the engines are cheap and light. That is one reason why, in practice, electric vehicles can accelerate much faster. For health and climate, the biggest advantage is clear: it can run on renewable energy and the motor itself has zero emissions.

Table 1.1 sums it all up and it is clear the electric motor is superior in every way. So why did we end up with the gasoline engine until know? To answer that question we must turn to the question of energy storage.

When you look at motors, the electric engine has the upper hand. But if you look at energy storage, the heat engine has the upper hand: fuel is a really marvellous way to store energy. And batteries compare very poorly to that. A visual comparison of these two storage methods is given in Figure 1.4.

Take Table 1.2. A lead-acid battery from 1900 stored only around 0.01 kWh per kg: that's more than 1000 times less! No wonder the gasoline engine won! A lead-acid battery at the end of the last millennium was better at 0.035 kWh per kg but that's still about 350x worse. A nickel-metal hydrate available at the turn of the new millennium stores 0.08 kWh. This is still 150 times less. But then people woke up, primarily because they needed lighter batteries for cell phones and laptops. And now a lithium battery as produced by the *Tesla Gigafactory* has about 0.25 kWh/kg, still 50 times worse. And in the near future (say within ten years) we can expect batteries that store double that, still 30 times worse.

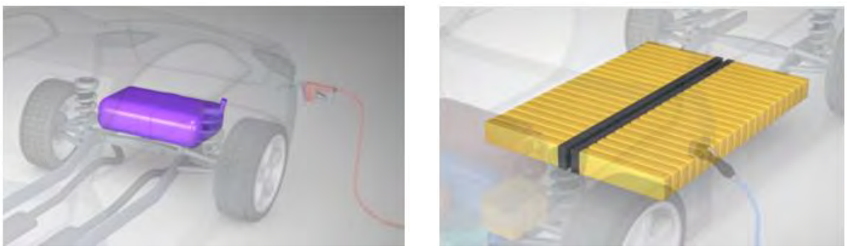


Figure 1.4 Fuel storage (on the left) vs battery storage (on the right)

Table 1.2 The extra weight of batteries (Lithium-air maximum energy content is theoretical)

Energy source	Year	Energy (Whr/kg)	Compared to gasoline
Gasoline	1900-20??	12 000	-
Lead-acid	1900	10	1200x worse
Lead-acid	2000	35	350 worse
NiMh	2000	80	150x worse
Lithium	2015	250	50x worse
Lithium	2025	400	30x worse
Lithium-air	????	12 000*	same

Theoretically, lithium-air batteries can even hold more energy than gasoline. And if we take the efficiency of the motor into account, 5 times as bad means the weight is the same. However, that is only a very long-term perspective.

Table 1.3 shows a simplified version of Table 1.2 to make it clearer how heavy these cars can be. How bad is that in reality, if we want to be able to drive a distance of 500 kilometres? In 1900 we would have needed to take 10.000 kg with us: a very big elephant. At the end of the last century, it was still a rhinoceros of 3000 kilos. The nickel-metal hydrate battery turned it into an 800 kg bison. But with the advent of the lithium battery, the 10.000 kg elephant has now turned into a 400 kg silverback gorilla. And within ten years it will be a 200 kg pig.

Now you might say: a 200 kg pig is still pretty heavy. But if you take the weight of the drivetrain into account, the electric drivetrain is so much lighter than the entire electric vehicle will actually be lighter overall in 2025! So the idea that batteries make electric cars heavy will soon be something of the past.

The reason that I put so much emphasis on weight is not just because it allows you to build lighter and nimbler vehicles. Just as important is the fact that something that is lighter needs less raw materials and in the end, that means it's going to be cheaper. So by making the battery plus drivetrain lighter for an electric vehicle, we can make it cheaper. And we are also saving the say 25 000 litres of fuel over the lifetime of the car.

Table 1.3 The extra weight of batteries, simplified (taking the drivetrain into account, the electric car is 200 kg lighter than an IC car)

Energy source	Year	Extra kg for 500 km	Equals
Lead-acid	1900	10 000	Elephant
Lead-acid	2000	3 000	Rhinoceros
NiMh	2000	800	Bison
Lithium	2015	400	Gorilla
Lithium	2025	200	Pig*

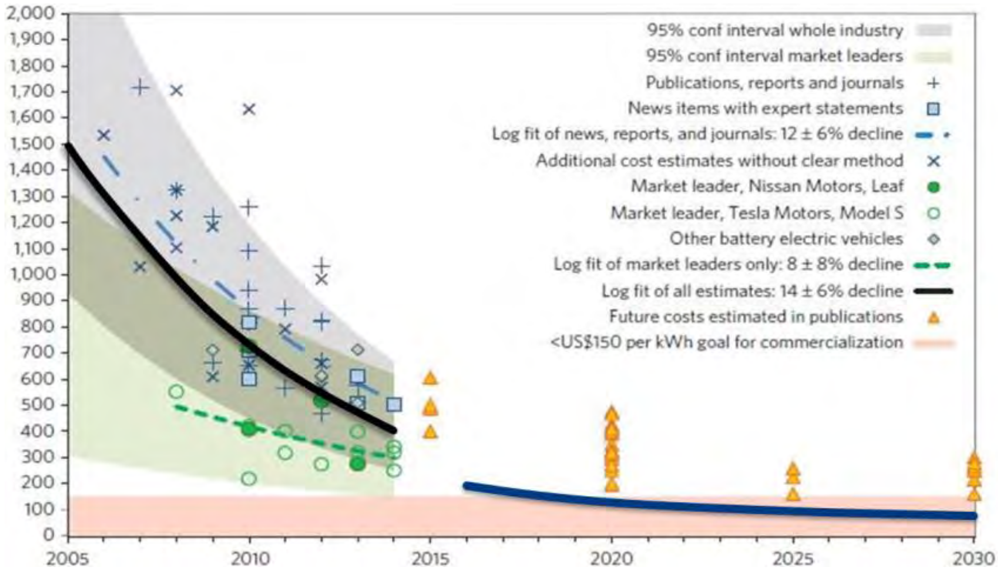


Figure 1.5 The rapidly falling cost of batteries. Adapted from [1]

So to wrap it up, there are essentially only two motors for cars: heat engines propel the car forward by burning fuel. Electric engines that use much more gentle and efficient magnetic fields. Electric engines are superior in almost every way: They are lighter, smaller, cheaper, require no maintenance, are four times more efficient, cause no exhaust, and can run on renewable electricity. The problem was that batteries used to be incredibly heavy. Heavier than an elephant! But due to incredible developments in battery technology in the first years of this millennium, the weight of battery plus drivetrain will soon be less for an electric vehicle. Taking the fuel savings and efficiency into account that means the electric vehicle will be much, much cheaper to own, as it is shown in Figure 1.5 [1]. So if you look at the fundamentals, the adoption of the electric vehicle is not a question of *if*. It is only a question of *how fast*.

Practice problems

Question 1

Determine whether the following statements are True or False with respect to a four-stroke engine .

1. On the first stroke, gasoline is injected into a chamber by opening a valve that is then closed again. ________
2. On the second stroke, the piston moves downwards and the gasoline is compressed. ________
3. On the third stroke, the energy in the fuel is harvested by igniting it. The resulting explosion drives the cylinder up and that produces a rotating motion. ________
4. On the fourth and final stroke, the energy burned is emitted. ________

Question 2

Fill in the blanks of the below paragraph with one of the following: **electromagnetic fields**, **kinetic energy**, **rotor**, **accelerate**

An electric motor works due to interaction between the ______ (1) of the stator and rotor. They are relatively light, compact and inexpensive as the ______ (2) is the only moving part. The average electric car is four times more efficient than the average conventional car as the energy efficiency of the motor can be close to a 100% and you can recover ______ (3) when braking. Oversizing an electric motor doesn't materially reduce efficiency and the engines are cheap and light. Therefore, electric vehicles can ______ (4) much faster.

Question 3

Electric cars have a simpler transmission and differential system when compared to a combustion engine car because:

- o The motor drive is a bidirectional power converter
- o It does not allow regenerative braking
- o Gears for electric cars are expensive

1.2 Comparing drivetrains

Are plug-in hybrid electric vehicles more than just a temporary stepping stone to fully electric vehicles? Why would you put up with the losses and complexity of fuel cell electric vehicle?

A quick recap of why we want to get rid of the internal combustion engine: burning fossil fuels causes global warming and the exhaust pollutes the environment. The engine of the car in Figure 1.6 throws away 75% of the energy it uses and produces noise as an unwanted by-product. Finally, the motor is heavy and expensive with lots of moving parts, requires all kinds of support like a gearbox and exhaust treatment system and requires a lot of maintenance over the lifetime of the car.

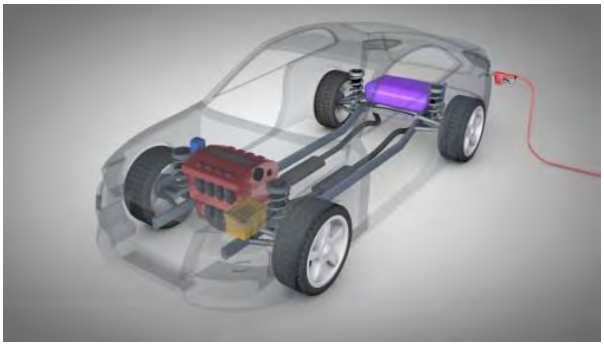


Figure 1.6 Internal combustion engine (ICE) vehicle schematic

Let us have a look at the depiction in Figure 1.7. Biofuels are sometimes seen as an alternative that makes the internal combustion engine unproblematic but of all the problems mentioned earlier it only addresses CO_2 emissions. Biofuels themselves are also highly problematic. There are many reasons but they are all related to the fact that biofuels are an incredibly inefficient way to use the energy of the sun. If you use solar panels, a 20% efficiency is normal and you end up with 14% of the power of the sun to drive the wheels. But photosynthesis is a much less efficient process. Although some biofuels might harvest a few percent, on average biofuels harvest less than half of a percent. And after refining, transport, and the inefficient internal combustion engine you typically end up with less than one-tenth of a percent. Apart from being hopelessly inefficient, biofuels need scarce water and fertile ground and are therefore – almost by definition – in competition with food and nature. Don't get me wrong: using biofuels from waste that cannot be turned into feedstock is a great idea! Some advanced biofuels from algae are also non-competitive with food and nature. And there are some agricultural practises like short rotational cropping that is mostly harmless. And there are some use cases that are very hard to achieve without biofuels. For example intercontinental flights with airplanes. But putting biofuels in cars creates more problems than it solves.

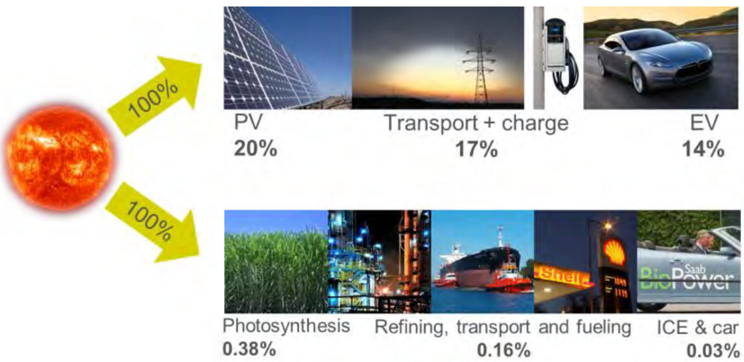


Figure 1.7 EVs vs biofuel efficiency (ICE) vehicle schematic

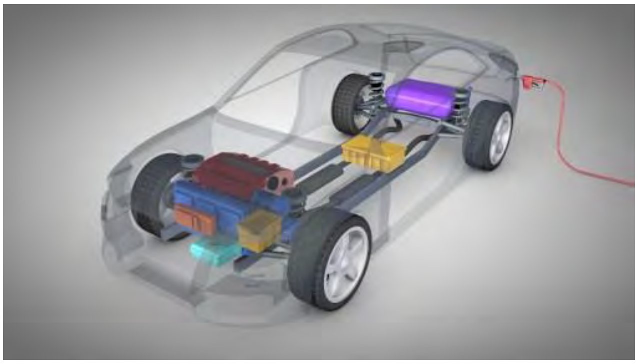


Figure 1.8 Hybrid Electric Vehicle (HEV) schematic

All these problems with the combustion engine and biofuels led us to the electric engine. And the first step we took was the hybrid electric vehicle.

As the name implies, the hybrid electric vehicle (in Figure 1.8) is a mix of a conventional vehicle with an electric vehicle. The battery and electric motor are scaled up and used instead of the gasoline engine on moments when the conventional engine is less efficient, such as during stop and go traffic. On other moments the gasoline engine recharges the battery. By using the electric motor in situations where the internal combustion engine is especially problematic the overall efficiency from the vehicle increases and the wear and tear on the combustion engine and brake pads decreases. Over the lifetime of the car, there is a clear financial advantage because the savings in gasoline or diesel easily outweigh the extra cost of producing this drivetrain. However, the advantages are limited. If you add hybridization to an already frugal gasoline engine you might save 10% or even 20% but that is about as far as savings can go.

The plug-in-hybrid electric vehicle, given in Figure 1.9, takes this a step further. It basically has both a conventional drivetrain and an electric drivetrain. It can get its energy from both fossil fuel and electricity.

Its biggest advantage is a long-range with a small battery while you can quickly replenish your energy storage using a gasoline station. Its biggest disadvantages compared to fully electric

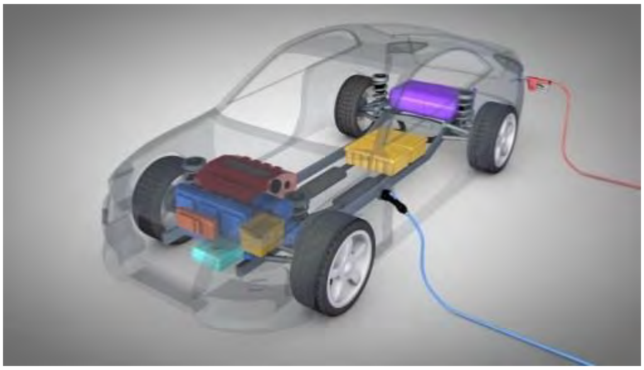


Figure 1.9 Plug-in Hybrid Electric Vehicle (PHEV) schematic

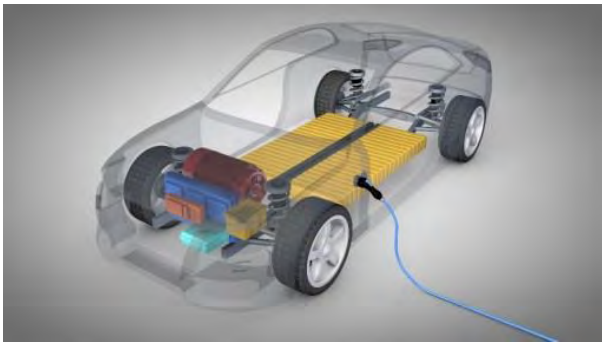


Figure 1.10 Full Electric Vehicle (FEV) schematic

are: A more expensive and complex drivetrain requiring more maintenance. More expensive in terms of energy used. Less CO_2 reduction and still some unhealthy exhaust. Now one of the things I'm asked most often is: do you think there is a future for plugin-hybrids. And my answer is: according to a lot of my peers the jury is still out. But I do a lot of total cost of ownership modelling myself, using my agent-based SparkCity model. And with the way battery prices are plummeting while fast-charging is becoming ever faster I really do not see a future for plug-in hybrids. But that is my opinion, coming from my research.

Now we move to the full electric vehicle. Here the conventional drivetrain is completely left out. So we have dumped the fuel tank, internal combustion engine, differential, gearbox and exhaust system.

The full-electric vehicle from Figure 1.10 ditches the internal combustion engine completely. It runs entirely on electricity and only uses the electric motor with all its advantages. One of the interesting things in terms of driving that one pedal driving is increasingly common. This means that you only use brakes in emergencies. Otherwise you simply accelerate by pushing the throttle pedal and decelerate by letting go of the throttle pedal. Of course braking this way has the added advantage of regenerating energy. The biggest disadvantage is that you need a large battery to get a decent range. My surveys lead me to believe that experienced EV drivers will be satisfied by a range of 400 to 500 km and simply won't see the advantage of a lager battery. That means that we should expect EVs with range similar to the Tesla models to dominate in the future. Of course full electric vehicles need fast charging capability. Currently that is often 50kW which translates to about 250 km of range in an hour of charging. But I expect that in five years' time the average for new cars will be 250 km of range in about 15 minutes.

The biggest reason for the rise of FEVs is not climate but money. Since they need only about one third of the energy and maintenance they are cheaper to own. And as battery prices go down, the sticker price becomes more reasonable too. To drive this message home and to show how much things are changing I included a simple calculation in Table 1.4.

It's based on an average car. For the US it would be pretty compact and for the EU it would be pretty big. We see that the electric drivetrain was a bit more expensive in the year 2000 but will be much cheaper in 2030. The low cost of electric drivetrains also explains why Tesla can offer supercar performance at a relatively low price. The battery is the biggie. In 2000 a range of 400 km cost as much as a 100 thousand dollars. But already we see a fivefold

Table 1.4 Full Electric Vehicle (FEV) cost comparison

Cost type	Gasoline	FEV 2000	FEV 2030
Drive train	$15k	$20	$5
Battery	$0	$100k	$10k
Fuel	$17k – 40k	$6k – 10k	$6k – 10k
Maintenance	$18k	$12k	$6k
Total	$50k – 73k	**DIS**ADVANTAGE $65K – 92K	ADVANTAGE $19K – 46K

reduction in price and in 2030 we expect a tenfold reduction. There is really no competing for the internal combustion engine with these overwhelming battery developments. Fuel is where the FEV starts to score. Over the lifetime of the car, you easily save anywhere from 10 to 30 thousand dollars. The savings in maintenance are also pretty substantial. The end result is that in 2000 the electric vehicle had a huge disadvantage but in 2030 it has a huge advantage. And if you want to drive a large or fun and sporty car, the advantage of the FEV will be even bigger.

I do TCO calculations a lot and the fundamental economics of the competing technologies are really clear. For this reason, I predict that the conventional vehicle and even the plug-in electric vehicle will quickly make way for the full electric vehicle.

One of the most interesting cases is the full electric heavy long-haul truck. A disproportionate amount of CO2 is emitted by these vehicles so if we can electrify them it would really make a big change for the planet. The heavy electric truck was long considered impossible to electrify but when you look at the economics, that assumption will be invalid pretty soon. Figure 1.11 features a detailed breakdown of the full electric trucks economics.

When you look as deeply into the TCO as I have you realise that the heavy electric truck is actually the best candidate for electrification. The electric vehicle must earn back the battery by using it as much as possible. And heavy trucks make a lot of kilometres which means a lot of potential energy-saving to pay back the battery. And because the focus of heavy trucks is

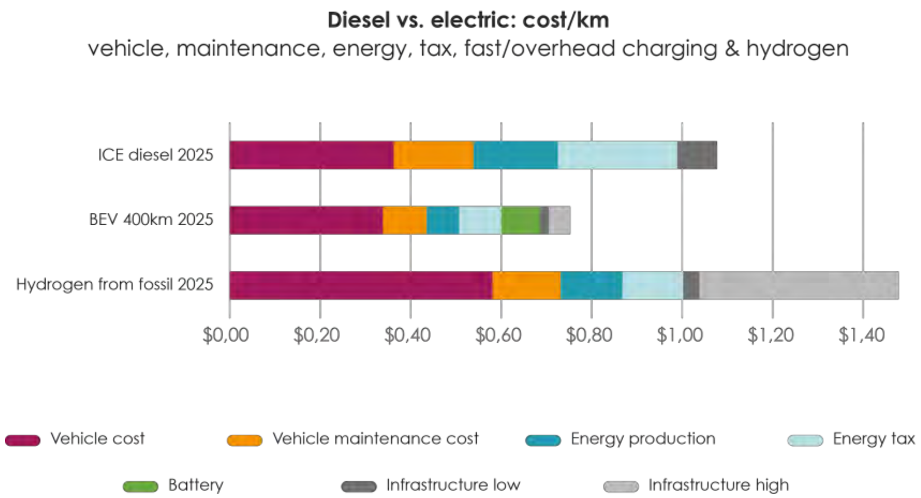


Figure 1.11 Full Electric Trucks economics

heavily on the total cost of ownership this market will flip as soon as the electric truck is cheaper. For that reason, I predict even faster adoption than for electric cars. One thing that still has to happen is fast-charging infrastructure for heavy trucks. You are talking about beasts with a power of 1 or even 2 megawatts! Although that is not unheard of for trains it is still new territory for road traffic. But I think it will happen because the economics are very good.

You can verify my assumptions because I detailed them in a series of blogposts. Bottom line is that my calculations indicate that diesel cars will be uncompetitive in 2025. And the charging infrastructure for heavy trucks has an even better business than fast chargers for normal cars [2].

Finally, there is the hydrogen fuel cell vehicle, for which a schematic is given in Figure 1.12. The first thing many people forget is that a hydrogen fuel cell vehicle is basically a battery electric vehicle with a range extender. So in terms of drivetrain, it's simplistic to see it as a competitor to the electric vehicle. And it has some clear advantages over the battery electric vehicle: You need a smaller battery. You can drive really long distances if you have enough space for the hydrogen tanks and you can refuel them very fast. The problem is that at the moment 90% of hydrogen is made from natural gas in a way that does not reduce emissions at all and even if we produce it in a green way, the efficiency is much lower.

Remember how I showed that solar panels captured 20% of the power of the sun and that the electric vehicle would have 14% left to drive the wheels? With hydrogen, a lot of energy is lost in the conversion from electricity to hydrogen and back again, as you can see from Figure 1.13. You end up with about one-third of the energy. In the far future maybe half. However, there is more to this story. If you have a large amount of solar and wind, say above 80%, chances are that you need to curtail – basically throw away – a lot of wind and solar. Storing this in hydrogen is of course much more efficient. And if you go for 100% solar and wind, you badly need some form of chemical storage to survive weeks or months of little wind and solar. Also, there might be locations that have abundant solar and wind but no connection to the grid. For example the outback of Australia. In those cases capturing the energy as hydrogen and transporting it using pipelines or container ships would be much cheaper than creating a grid connection. So hydrogen has a place in the renewable economy of the future. I am not sure at all that hydrogen in cars is a logical and economic solution but the jury is still out on this one.

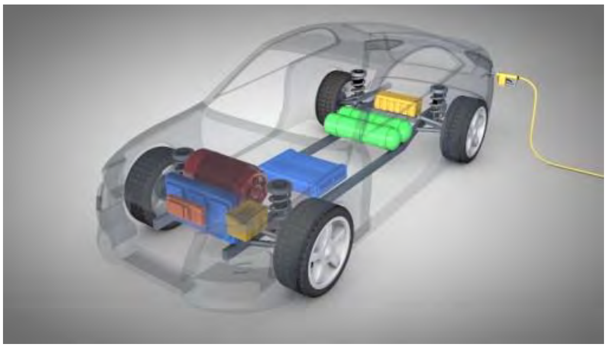


Figure 1.12 Hydrogen Fuel Cell Electric Vehicle (FCEV) schematic

Figure 1.13 Hydrogen vs EVs efficiency

What will determine the future of hydrogen are the price developments in fuel cells, storage and electrolysis so I for one will be following this field with a lot of interest and I hope we are smart enough to fund a lot of R&D.

That brings me to my conclusions. All the hybrid drivetrains are complex, especially compared to the fully electric vehicle. As battery prices continue to plummet there will be a move from hybridization to more electric and my personal expectation is that we will skip the plug-in hybrids and go directly to the full electric vehicle. Not only for passenger cars but especially for heavy trucks. If you look at the fundamental economics of the different drivetrains one thing is very clear: the internal combustion engine is on the way out.

Practice problems:

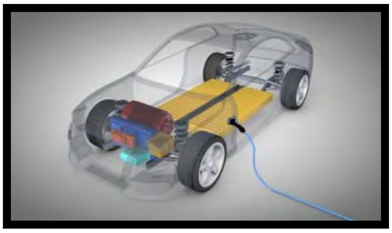
Question 1

In the lecture, we saw that putting biofuel in cars creates more problems than it solves. There were reasons provided to support that statement. Please select the two correct reasons that support the statement.

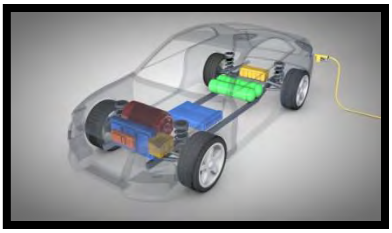
- ☐ Highly problematic as biofuels are an incredibly inefficient way to use the energy of the sun.
- ☐ Need scarce water and fertile ground and are therefore in competition with food and nature.
- ☐ Biofuels are produced from waste that cannot be turned into feedstock

Question 2

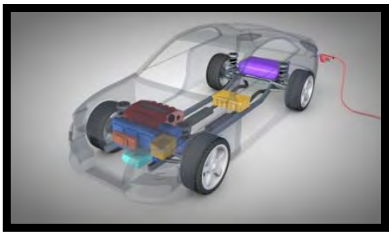
Match the vehicle type to the correct picture



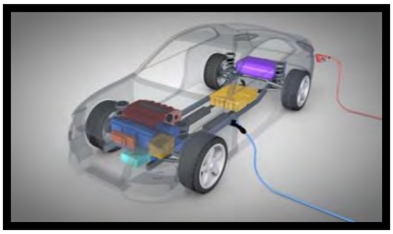
- Hybrid electric vehicles



- Plug-in hybrid electric vehicles



- Full electric vehicles



- Fuel cell electric vehicles

Question 3

a. In the lecture, we saw that 50 kW charger translates to about 250 km of range in an hour of charging. In five years' time, it is estimated that the average for new cars will be 250 km of range in about 15 minutes.

What will be the capacity of the charger in the latter case?

- o 0.2 MW
- o 2 MW
- o 20 kW

b. Assume that you are making a trip from Amsterdam to Berlin in your electric car, the distance is approximately 550 kilometres. You will be spending time on charging. The total waiting time will vary based on the capacity of the charger. You began the journey with a fully charged car that can go on for a range of 300 kilometres.

Choose which options follow with above statement. Note: More than one option can be true.

- ☐ I need to make one stop and wait for 15 mins at 0.2 MW charging facility.
- ☐ I need to make one stop and wait for 60 mins at a 50 kW charging facility.
- ☐ I need to make one stop and wait for 30 mins at a 50 kW charging facility.

1.3 Sizing of the EV powertrain

1.3.1 Resistance forces

In this lecture, we will talk about how to estimate the forces on the vehicle and the power that needs be delivered by the powertrain to control the vehicle speed. We will discuss the forces on the electric vehicle while it's driving, and how to use traction to control vehicle speed.

(1) Rolling resistance force

The rolling resistance force occurs due to the friction between the tires and the driving surface. The rolling resistance force is zero at standstill. When the vehicle starts moving, the rolling resistance force acts in the direction opposite to the direction of motion and can be calculated by the rolling resistance coefficient Cr multiplied by the normal force between the vehicle and the road. For a flat surface, the normal force is the vehicle mass m times the standard gravity g.

In the case of a road with an inclination angle, the normal force becomes the weight m.g multiplied by the cosine of the road angle. It is important to note that the rolling resistance force is independent of the vehicle speed, and it is always opposite the driving direction. The coefficient Cr should be low so as to keep the frictional losses low. For modern cars, it’s typically around 0.01 to 0.02.

(2) Aerodynamic drag force

As the vehicle speed increase, the aerodynamic drag force opposes the vehicle motion as the air as is forced to flow around the moving vehicle. It can be calculated as the product of the aerodynamic drag coefficient Cd the front area of the vehicle Af, the air density and the square of the vehicle speed v, divided by 2.

It is hence important to note that the aerodynamic drag in independent of vehicle mass but has a strong dependence on the vehicle speed. That is why in a car, the aerodynamic drag force is higher than the rolling resistance force when the speed is above about 70 to 80 km/h.

Secondly, the coefficient of drag is typically about 0.25 to 0.35 for a modern car. SUVs, with their typically boxy shapes, have coefficients in the range of 0.35 to 0.45.

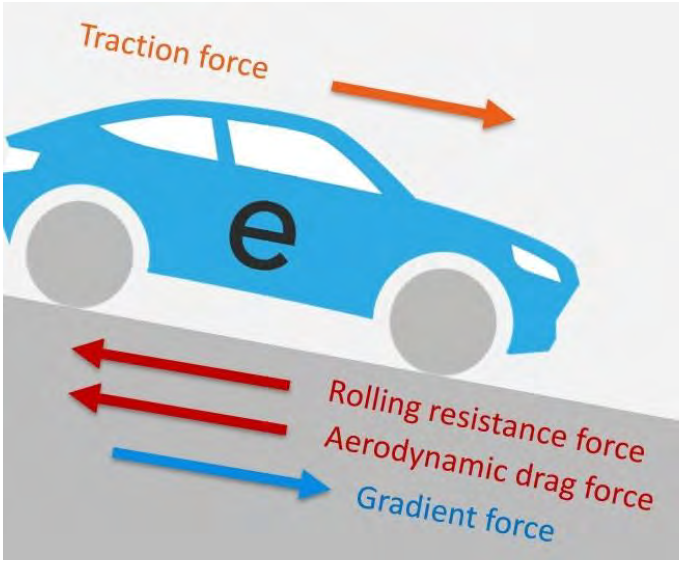
(3) Gradient force

The third force that acts on a vehicle is the gradient force, and it occurs when the vehicle is driving on an uphill or a downhill road. The gradient force is due to the longitudinal component of gravitational force, namely mg where theta is the inclination angle of the road. As seen earlier, the cosine component of the gravity contributes to the normal force and the corresponding rolling resistance force.

The gradient force and the angle theta are negative when driving downhill, and positive when driving uphill. Road gradients are expressed as a percentage in terms of tangent theta and have a value typically between plus or minus 10%.

1.3.2 Net force on the vehicle

If we now consider a vehicle moving on an inclined surface, then the aerodynamic drag force, the rolling resistance force and the gradient force act on the vehicle. If we now include the traction force provided by the vehicle powertrain, then the net force on the vehicle is the difference between the traction force and the sum of the forces due to the aerodynamic drag, the rolling resistance, and the road gradient.



By Newton’s second law, the net force is equal to the product of the vehicle mass and vehicle acceleration. Therefore, we can control the vehicle acceleration and thereby the speed by controlling the traction force that the powertrain produces. The traction force is in the driving direction most of the time, but it can be zero when the vehicle is coasting or even negative when the powertrain is under regenerative braking.

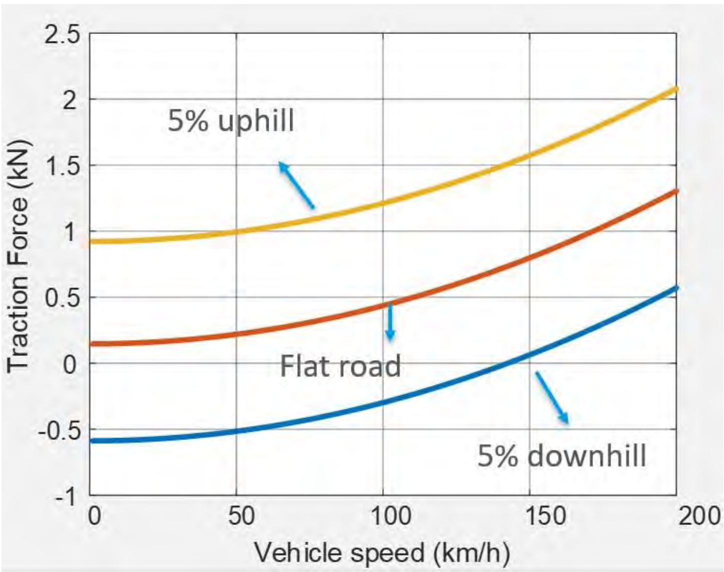
If we now expand the equation for the traction force, we can see the factors that influence the vehicle forces: the vehicle mass and road angle affects the rolling resistance and gradient force, vehicle speed decides the aerodynamic drag force, and the rest of the traction force decides the vehicle acceleration. If we need to estimate the power delivered by the powertrain, then we need to multiply the traction force with the speed of the vehicle.

It is important to realize that in this lecture, we only take into account the forces in the forward and reverse direction, as they influence the powertrain. The forces in other directions are neglected for simplicity. Secondly, the forces in the vehicle are assumed to be acting at one point. In reality, the forces are distributed over the vehicle.

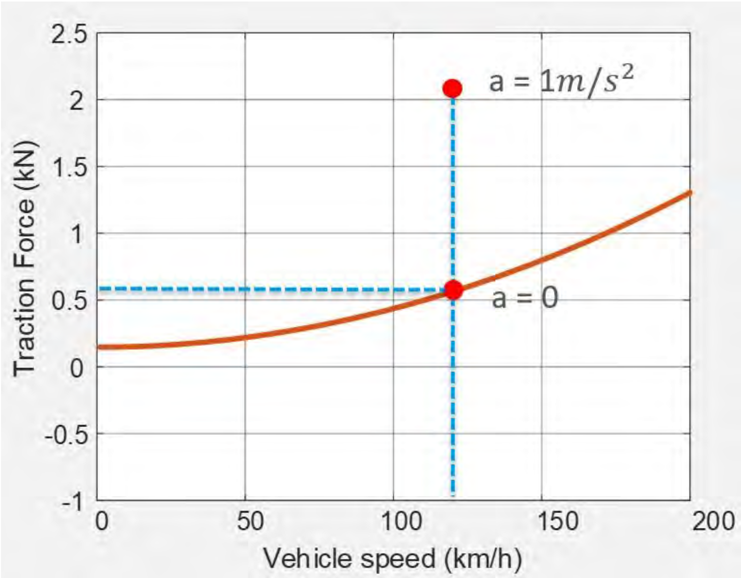
Let us now look at a force/speed diagram of a vehicle with a mass of 1.5 ton, frontal area of 2.5m^2 and the speed range of 0-200 km/h. From the formula for the traction force, we can calculate the force at each speed level for zero vehicle acceleration. Those points make a force/speed curve of this car. When the speed is close to zero, then the traction force is used to overcome the rolling resistance force. As the speed increase, the traction force needed increases fast, as the aerodynamic force increase with the square of the speed.

1.3.3 Operating point

Next, let us investigate 3 road conditions, a flat road, a 5% gradient uphill, and a 5% gradient downhill. We can see in the downhill condition, the traction force needed for low speeds is negative, as the gradient force is larger than combined rolling resistance and aerodynamic drag forces. On the other hand, the uphill gradient requires a significantly higher traction force for the same speed than the 0% or downhill gradient.



Finally, let’s consider the case when the vehicle has a finite acceleration. This is the speed/force curve for the same car with 0% gradient and zero acceleration. Since the mass of the car is 1500kg, for every 1m/s2 acceleration, an extra 1500N traction force from the powertrain would be required.



Besides the traction force, the EV battery also provides power for the vehicle auxiliaries, like heating, air conditioning, lighting, wiper etc. Hence, the net power delivered by the traction battery, Pbatt is the sum of the traction power and the auxiliary power.

To conclude, the forces acting on a vehicle when it's driving consist of the rolling resistance force, the aerodynamic drag force and the gradient force. The drive train provides the traction force, which can be controlled to change the vehicle acceleration and hence the speed.

Practice problems

Question 1

The car has a total weight of 1200*kg* and frontal area of 2.0*m*2. The rolling resistance *cr* is 0.015, air density is 1.2*kg*/*m*3 and aerodynamic drag coefficient *cd* is 0.30. When the car is running at 50*km*/*h* on a flat road, what is the rolling resistance force and aerodynamic drag force on the car?

- (•) 176.4N, 46.3N
- ( ) 176.4N, 600N
- ( ) 152.8N, 46.3N

Question 2

In the car from Question 1, what would happen to the rolling resistance and the aerodynamic resistance if the vehicle mass increase 50% and frontal area decrease 20%

- [ ] The rolling resistance remains the same.
- [ ] The rolling resistance increase 50%.
- [ ] The rolling resistance decrease 20%.
- [ ] The aerodynamic resistance remains the same.
- [ ] The aerodynamic resistance increase 50%.
- [ ] The aerodynamic resistance decrease 20%.

Question 3

The vehicle from Question 1 has a traction force of 600N. What will happen to the car speed? You can get the answer by calculating the net force on the car.

- ○ The car speed will increase from 50k/m.
- ○ The car speed will decrease from 50k/m.
- ○ The car speed will remain the same.

Question 4

If the vehicle from Question 1 is driving in a uphill road with 0.1 gradient, what is the traction force needed to keep have a $1m/s2$ acceleration? _____

1.4 Types of electric motors

We already saw that if you just look at vehicle motors, electric motors are vastly superior to gasoline and diesel engines. They are much lighter and cheaper. They need no maintenance. And most importantly, electric motors are three times as efficient. But which electric motor is best? To answer that question, you can look from many different perspectives. Electrical engineers have dozens of ways to classify the motor which can be utterly confusing. Mechanical engineers look at properties like size, weight and maximum torque. Practical builders look at things like availability, simplicity and robustness. Economists and business people would be interested in the purchase price and efficiency. Finally, people interested in the environment are interested in the use of scarce earth metals and efficiency as it pertains to CO_2 emissions. Covering all motors and all angles are impossible so we will focus on the three types of electric motors used in almost all-electric vehicles.

There are literally dozens if not hundreds of ways to classify electric motors. But if you look at the literature on electric vehicles, there are only three types of drives that are widely used as is shown in Table 1.5 from a 2014 overview [3]. That is why we will focus on the induction motor, permanent magnet motor and synchronous reluctance motor.

Table 1.5 Commercial EVs categorized under three types of motors

Induction	Permanent Magnet	Synchronous Reluctance
Ford ECOstar (1992)	Nissan Al tra (1997)	Holden Ecommodore (2007)
Ford Ranger EV (1999)	Toyota Prius (2004)	Renault Fluence ZOE (2011)
GM EVI (1999)	Mitsubishi MiEV (2009)	
Tesla Roadster (2008)	Nissan Leaf (2010)	
Ford Think City (2008)	Tata Indica Vista EV (2011)	
Fiat Panda (2009)	Fiat Peugeot ION (2011)	
Chevrolet Silverado (2010)	Chevrolet Volt (2011)	
Ford Focus Electric (2011)	Hyundai Blueon (2012)	
REVA NXR (2011)	Honda Fit EV (2012)	
Tesla Model S (2012)	Honda Civic (2013)	
Honda Fit EV (2012)	Volkswagen eGolf (2015)	
Toyota Reva 4 (2012)	Chevrolet Bolt (2017)	
Mahindra Reva e20 (2012)	Tesla Model 3 (2017)	

Before we proceed to motors used in electric vehicles, let me start my explanation with the classic and simple brushed DC motor, which is shown in a schematic drawing in Figure 1.14. This motor has a fixed part, called the stator – because it is static – that contained magnets. It also had a rotating part, called the rotor – because it rotates – that contains electric coils. Stator – fixed, and rotor – rotate. When you connected the coil in the rotor to the direct current produced by a battery, the current from the battery would produce a magnetic field in the rotor.

The interaction between the magnetic field from the electric coils and that of the permanent magnets in the housing – the stator – would lead the rotor to turn. After turning a bit the magnetic field in the rotor would start to get aligned with that in the stator. But before that happens, the commutator switches the polarity of the connection between coil and battery. The reversed polarity leads to a new magnetic field in the rotor and the rotor will keep rotating. A lot can be said about these motors but we will not because they are no longer used in commercial electric vehicles. That is largely due to the brushes needed for the commutator to work. These brushes can malfunction and cause sparks, they must be regularly replaced and they lead to a loss in efficiency. They also need a starting mechanism to avoid burning out.

A better alternative was invented by Nikola Tesla. This AC Induction motor – or Induction motor for short – shown in Figure 1.15 needs no permanent magnets. Instead, the magnetic field is produced by a current that flows through the windings in the housing or stator. The magnetic field from the stator will induce a voltage and current in the windings of the rotor.

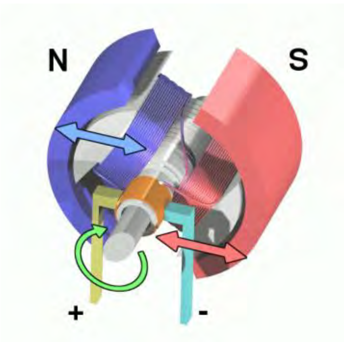


Figure 1.14 Brushed DC motor configuration

Figure 1.15 Induction motor

That is the reason why it is called the induction motor. This, in turn, leads to the rotor producing its own magnetic field. And this magnetic field will make the rotor turn so as to align itself with the magnetic field from the stator. Now, Nikola Tesla had a second trick up his sleeve.

He connected the stator to alternating current which means the magnetic field in the stator was also alternating. If you do this cleverly enough you can create a so-called rotating magnetic field or RMF. And the rotor will follow this rotating magnetic field in the stator, without the need for a commutator with brushes. Since the rotor follows the rotating magnetic field only after it has created an induced electric field itself, it is always lagging behind a bit. The amount that the rotor lags behind is called “slip”. This slip causes the rotor to always be out of sync with the rotating magnetic field a bit. That’s why an induction motor is called an asynchronous motor.

The first AC Induction motors ran at a constant speed. But later it became possible to vary the frequency of the alternating current using a so-called variable frequency drive or VFD. Using the VFD you can vary how fast the magnetic field turns by varying your alternating current or AC frequency. Other names for VFD are Variable Speed Drive, Adjustable Frequency Drive, AC drive converter. It’s been very successful: I estimate that in 2017 over 90% of industrial motors were still induction motors. It was also used in the first range of cars from the Tesla motor company.

The induction motor has many advantages: the most important might be that it is so very simple to construct. It also has the lower sticker price because it has no permanent magnet, no brushes, no position sensor, no starting mechanism since it is self-starting.

Speed control is easy. You simply control the frequency of the alternating current with a variable frequency drive. But there are some disadvantages: the induced currents in the coil cause efficiency losses. The induced losses also mean induced heat in the rotor and thus the need for cooling the rotor. It is also not the lightest nor most compact electric motor.

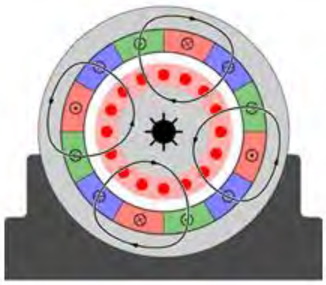


Figure 1.16 Permanent magnet motor

Recent advances in material science have made it possible to produce very powerful permanent magnets using neodymium. If we construct a rotor with permanent magnets we no longer need to induce a magnetic field in the rotor, as given in Figure 1.16. This avoids losses and heat development in the rotor. Because of all this, permanent magnet motors are currently the smallest and lightest electric motors you can buy. Because the rotor is already magnetized it is always in sync with the rotating magnetic field. That is why permanent magnet motors are also classified as synchronous motors. Often the rotor with the permanent magnets on it runs at the outside. This is called an out-runner. An out-runner can deliver higher torque at lower speeds. Sometimes the rotor and the permanent magnets run at the inside and this is called – you guessed it – an in-runner. An in-runner can quickly spin up to high speeds. So when high speed is not a problem, an in-runner can provide the same power in a smaller, lighter and cheaper package.

The permanent magnet motor is increasingly used in all kinds of high-performance applications Electric vehicles are no exception. Although I cannot statistically prove it yet it seems more and more electric vehicle manufacturers are replacing induction motor with permanent magnet motors. A good example is Tesla. Although the company is named after the inventor of the induction motor, its new models use the permanent magnet motor.

The advantages of the permanent magnet motor are that it is the lightest and smallest motor. It is also the most silent and efficient motor. The biggest disadvantage is that it needs these scarce earth metal magnets and they are expensive. They are also a bit more complex to run, requiring a position sensor, starter mechanism and more advanced controller.

A recent development is a motor that tries to combines the best of both worlds: the synchronous reluctance motor, shown in Figure 1.17. It has a rotor that contains metal that is formed in such a way that it wants to align itself naturally to the surrounding magnetic field. So it does not need to produce its own electric field through induced currents like the induction motor. This means fewer losses. And it does not need permanent magnets which makes it much cheaper than a permanent magnet motor.

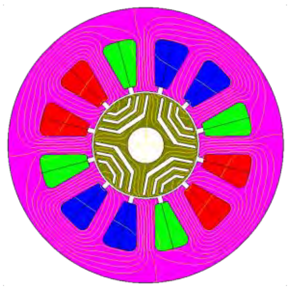


Figure 1.17 Synchronous reluctance motor configuration

This bestows the synchronous reluctance motor with some important advantages: it has torque and efficiency (especially at higher speed) that is comparable to permanent magnet motors. It does not need permanent magnets which makes it more rugged, cheaper and better for the environment. However, it has some disadvantages. Efficiency at a lower speed can be a bit lagging compared to a permanent magnet motor. There are higher inherent noise and torque ripple. However, as rotor design improves and especially as advanced motor controllers and algorithms improve the noise and torque ripple might be almost eliminated. All in all, it is still early days for the synchronous reluctance motor but an increasing number of publications seems to indicate that there is so much room for improvement that it could indeed become a motor that combines the best of both worlds.

Figure 1.18 sums it all up. We based the graph on an overview from Kumar and Jain [3]. If reliability and sticker price are your main concerns, look no further than the induction motor. But if you have other concerns as well, there are better alternatives. If all you care about are maximum performance in terms of size, weight and efficiency, the permanent magnet motor is your best bet. On a side note: even though the permanent magnet motor is the most expensive one in this comparison, it is still much cheaper per kilowatt than conventional gasoline or diesel motor. But if you are looking at the best compromise on all aspects, and if you are not afraid of advanced controllers, there is a good chance that the synchronous reluctance motor is the best choice for your application. My personal prediction is that synchronous reluctance motors will improve more and more though advanced rotor designs

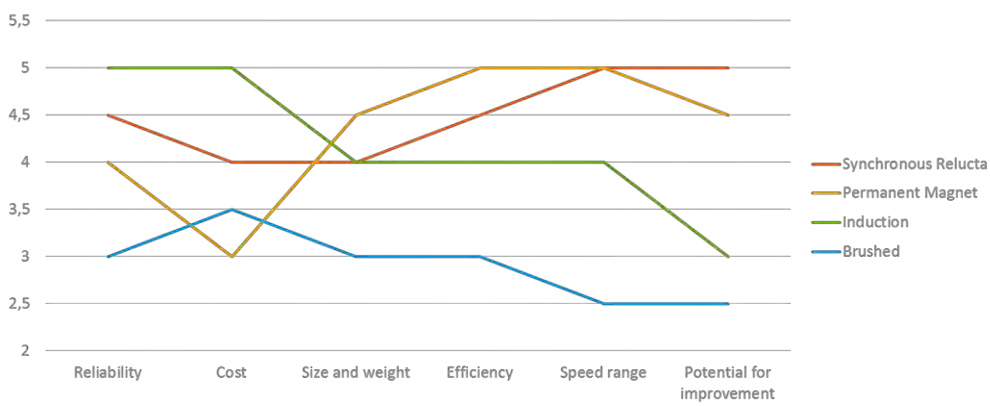


Figure 1.18 Final motor comparison

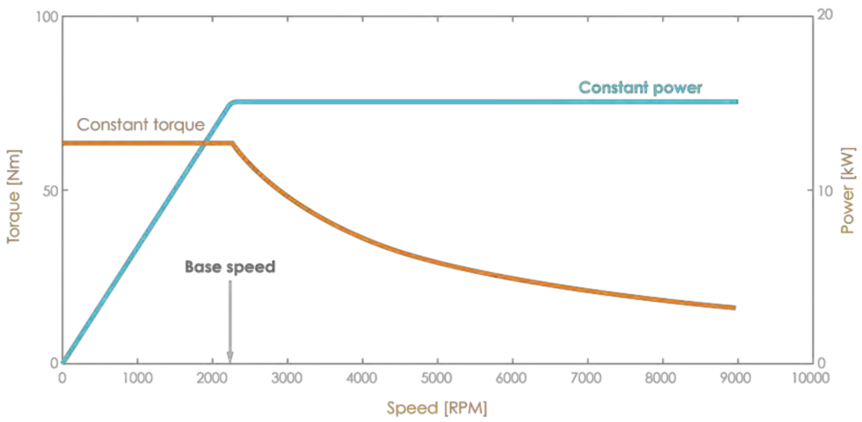


Figure 1.19 Torque-speed characteristics of a motor

and controllers that minimize torque ripple and thus noise, until they match permanent magnet motor performance, at a cost and reliability that matches the induction motor. Time will tell if I'm right on that one. That concludes this introduction into electric motors for the electric vehicles. Of course, there are literally thousands of different motors out there so choosing will never be easy but I hope this at least gives you some fundament from which to proceed.

With reference to Figure 1.19, electric machines are sometimes characterized with respect to the speed range, constant torque range and constant power range. At speeds above the base speed, the torque decreases resulting in a constant power. The effects of extending the constant power operating region of an electric machine on the performance of a simple BEV model were examined in [4].

Performance parameters examined were acceleration time and distance, and overtaking time and distance. For high-speed cruising, it was generally found that electric machines with higher extended range ratios (ratio of constant torque region to constant power region), the acceleration time and distance increased.

In the last part of this section, we will have a look at the different motor layout configurations. Indeed, a number of motor configurations are possible for EV's, which provides more flexibility

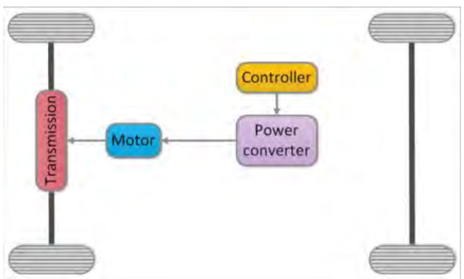


Figure 1.20 Single motor configuration

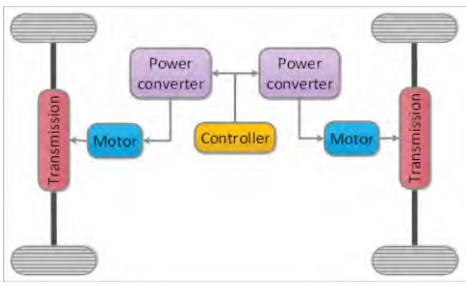


Figure 1.21 Dual motor configuration

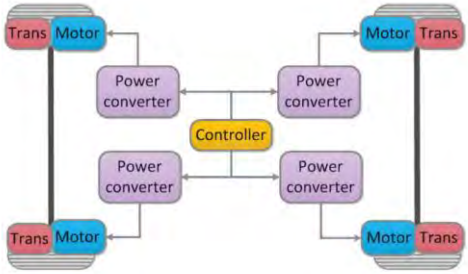


Figure 1.22 In-wheel motor configuration

for the driveline layout. **Single motor configurations**, in Figure 1.20, use one motor that drives either the front or rear axles.

With a **dual motor configuration**, shown in Figure 1.21, two motors are used to drive the EV and this can be done in different ways. One possibility is that one motor can power the front axle and the other the rear axle. Second, both the motors can be placed on either the front or rear axle to provide increased torque compared to the single motor configuration. Alternately, the two motors can be used to drive the left and right wheel independently on either the front or rear axle, meaning there is more control over the vehicle when cornering/turning. Although most EV manufacturers currently adopt the single motor configuration, the dual-motor configuration has also been used for vehicle models with higher torque capability.

Using a separate motor to drive each of the four wheels independently is another possibility. This can be achieved using an in-wheel where the motor that is placed within the wheel of the car. The **in-wheel motors** can be either geared or gearless, as represented in Figure 1.22. The gearless option has the potential to improve the overall efficiency of the driveline, but additional controller complexity and hardware required to make such a system more complex.

Practice problems

Question 1

The Tesla Model S (2012) car had an electric motor but the Tesla Model 3 (2017) has a different motor.

a. Name the electric motors in Tesla Model S (2012) and Tesla Model 3 (2017) respectively.
   - o Induction and Permanent magnet motor
   - o Permanent magnet and Induction motor
   - o Induction and synchronous reluctance motor

b. Based on the lecture, what could be the reasons Tesla decided to switch to a new motor?
   - o The permanent magnet motor is the lightest and smallest motor. It's also the most silent and efficient motor.
   - o The induction motor is complex to run, requires a position sensor and a more advanced controller.

Question 2

Below you see working principles of various motors. Choose for each of the described principles the corresponding motor: **induction motor**, **DC brushed motor**, **synchronous reluctance motor**.

1. The stator contains magnets and rotor contains electric coils. The interaction between the magnetic field from the electric coils and that of the permanent magnets in the stator leads the rotor to turn. After turning a bit, the magnetic field in the rotor would start to get aligned with that in the stator. But before that happens, the commutator switches the polarity of the connection between coil and battery. The reversed polarity leads to a new magnetic field in the rotor and the rotor will keep rotating.

   ____
2. The magnetic field from the stator will induce a voltage and current in the windings of the rotor. This, in turn, leads to the rotor producing its own magnetic field. And this magnetic field will make the rotor turn to align itself with the magnetic field from the stator. The stator is fed with alternating current which means the magnetic field in the stator was also alternating. This creates a so-called rotating magnetic field or RMF. The rotor will follow this rotating magnetic field in the stator, without the need for a commutator with brushes.___________________
3. It has a rotor that contains metal that is formed in such a way that it wants to align itself naturally to the surrounding magnetic field. So, it doesn't need to produce its own electric field through induced currents and it doesn't need permanent magnets.

   ____

Question 3

Determine if the below statements are **true** or **false**.

1. Since the rotor follows the rotating magnetic field only after it has created an induced electric field itself, it is always ahead a bit. The amount that the rotor is leading is called "slip". This slip causes the rotor to always be out of sync with the rotating magnetic field a bit. That's why an induction motor is called an asynchronous motor. _______
2. In permanent magnet motors, because the rotor is already magnetized, it is always in sync with the rotating magnetic field. That's why the permanent magnet motors are also classified as synchronous motors. ______
3. The rotor with the permanent magnets on it running at the outside is called an out-runner. An out-runner can deliver higher torque at lower speeds. _______

Question 4

What are single motor configurations?

- o Each wheel has a separate single motor.
- o Single motor configurations usually drive either front or rear axles, with the wheels driven synchronously.

- One axle is driven and each wheel on one axle can be driven independently.

1.5 Case study: Carver

Carver is a Dutch manufacturer of sustainable mobility solutions to travel faster, smarter and more sustainably from door to door. The electric Carver is designed as a sustainable transport alternative for commuters and urban professionals. An innovative, compact city vehicle as a solution for the jammed traffic in and around cities. The Carver is equipped with a unique tilting technology that unites the advantages of a car and a scooter in the spectacular new driving experience.

Now that we have learned about the motor, drivetrain and energy storage of an EV, let us look at how these concepts are used in the real world. For this, we have a case study with Chris van den Brink, technical director of Carver (https://carver.earth/en).

1.5.1 Company introduction

Hi, I am Chris van den Brink. I am the technical director of Carver. Carver started 20 years ago with the concept idea, “Look at the vehicles on the road.” Everybody, let’s say 80 per cent of vehicles have only one person sitting in the vehicles which is suitable for driving around five. There was our basic idea that there should be a vehicle which is specifically suitable for driving one or one-plus-one persons. Same as if you are in your kitchen, say if you want to bake only one egg, you only take a small pan. And if you are with your whole family, you take a big pan. In the car we always take a “big pan” and drive around, only to bake a “small egg in a big pan”. No! So this was our basic philosophy of Carver. So we decided to make “small pans” in the vehicles.

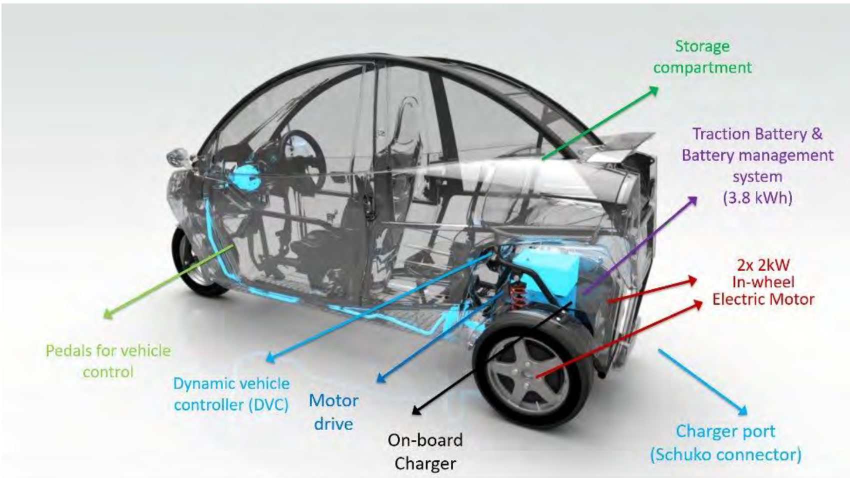
Then we came up, “okay, it’d be better if we had a vehicle which was narrow.” Because you got the, say, less aerodynamical drag, not smart having sit where you side-by-side, but rather behind each other. Then we faced the problem, if you make a vehicle which is narrow, you fall off. Our basic first prototype which we made was a motorbike, an enclosed motorbike, but the problem with motorbikes is at low speeds, you have to put your feet on the ground, so we thought we are going to solve it with side wheels which came down. We did a lot of test driving, but it was very difficult to drive, first of all, you don’t have control over the wheels, long story short, you cannot make the wheels automatic because you don’t know where to drive or know what the driver wants to do. And second, we noticed that if you are sitting in a vehicle like a car, steering like a car and the comfort of a car, it is very difficult, with especially a high centre of gravity, to drive like a motorbike. So we had a lot of crashes with that vehicle with the sidewheels. Then we came up with an invention that it should automatically tilt.

We are here at the Carver R&D centre. Our production facility is in the north of Holland, here in South Holland, we do all the developments. I am very proud to say that we do almost all the developments ourselves, even our circuit boards. For instance, this is our BMS (Battery Management System) circuit board which we have developed from scratch ourselves. We are also capable of making first prototypes ourselves in house, test it modify it, test it modify it and when it is finished as it is now, we ship it to the manufacturer and say “Hey, this is what we want, we have already tested it. Give us a good price and we would like to order large volumes.” We are flexible to choose any manufacturer we desire. So we have done our BMS. We have dealt with our motor controllers, even with our motors, which we developed partly ourselves in which the mechanical things we did ourselves. We used already existing wire and magnet pattern which we have used in the motorbike where the motorbike had two shafts and we wanted to have a motor attached to each shaft, right here. So yeah, at this site, we also do all our electronics.

So if you have questions regarding the electric vehicle, I’d always advise just do it, don’t be afraid of electric vehicles, it’s not that difficult, it’s not that complicated. Let’s say in combination, some parts are very complicated like BMS or m-bus or whatever, but basically it is quite simple. Basically, you got an electric cell, you got two motors, a motor control between it and that’s it. But a lot of software involved in having all the electronic devices talking to each other, that’s quite a challenge for you as viewers and learners and students. I think it’s a very challenging thing which definitely is the future. So keep continuing!

1.5.2 Carver electric vehicle structure

In this block diagram, you can see the layout of the components in a Carver electric vehicle.



We can see the 3.8kWh battery and battery management system is located in the back of the car, between 2 wheels. The motors, 2kW each, are inside the wheels.

In the following video, we will see Chris present the structure of a Carver electric car.

Here you can see the black box, where the batteries are located. In combination on top of that box is the BMS, the battery management system. It’s all in this box! All the high voltage is also in this box. We have no real high voltage, we got 60, below 60 volts. The reason why we chose below sixty volts is everybody can work with it. It’s no danger, let’s say it’s not high voltage level. So that’s the batteries. Then we have here the wheel head motors which are in the wheels, one on the left, one on the right. In order to make it tilt automatically, we have got here, the rear gear balance track, with tilt motor in the centre. So the batteries are located in this black box, 16 cells just below 60 volts and we got one wheel motor in the wheel here and the other one over here. If you drive and the battery is empty, you can charge with the battery plug on this. You can take out and you can put it any socket and it will start charging. You can see it 96 percent full now.

1.5.3 How does EV work?

In this video, we asked Chris van den Brink, technical director of Carver why you should switch to EVs, how Carver differs from other electric vehicles, Carver's use scenarios and more.

- From the perspective of technology and as an electric vehicle manufacturer, what makes an electric vehicle better than a fossil fuel-powered vehicle?

Very good question I think in the future we should all drive electric and the main reason is that we got a big CO2 problem. We take oil out of the ground burn it and it will definitely take us back to the dinosaurs’ age where we got too much co2 in the air. So if you want to save the world we have to drive electric because with electric you can use any source of energy. You can use water energy, power energy, you can use of windmills, you can use solar panels and we even can everything.

- Reasons to buy an EV?

Now I mean electric is the future. It's not that we have to go a step down it's a step up the driving behaviour. You get a lot of torque so it's very comfortable to drive you don't have to shift it's very compact so it's the way for the future.

- The decision to make carver a fully electric vehicle rather than a plug-in hybrid?

The basic idea with this car concept is that we wanted to make a city vehicle which, what, price concern is between a scooter and a car so. And because it's very aero-dynamical so we need not as much energy to propel it. So with a quite small battery pack, we can already achieve two and a half hours of driving with this vehicle. And that's for one day more than enough for the use

- Which parts of the electric car have huge potential for improvement, both technology-wise and cost-wise?

Of course, the batteries, I mean, for the electric vehicle is the most expensive part of the vehicle and had to make it for large volumes you need to bring the price down as much as possible. So that's why I think that electric vehicles should be very light, it should be very aero-dynamical because yeah, the battery is the most expensive part of the vehicle.

- Compared to a conventional car, which parts of an electric car are maintenance-free and which parts still require maintenance?

Almost everything is maintenance-free apart from the brakes, okay we still break with regen so we use fewer brake pads but eventually the brakes wear out. And second the tires they wear down as quickly as normal so it's brakes and tire. And all the other things, I think so, are maintenance-free.

- With the increasing availability of charging infrastructure, is a long-range EV with a big battery needed?

Well you see more and quicker charging, to be honest for a normal vehicle, this is a city vehicle it's low-speed but for normal high-speed vehicles depends on how fast you charge

- Would we see the AC onboard charger of EVs being completely moved out, like what we see in laptops?

Well, to be flexible I think you both need the DC fast charger and AC slow charger, for instance at my house there is no charging station so I have to do with AC charger.

- Technical advantages and disadvantages of a Carver compared to a conventional family electric car and compared to the other two-seater electric vehicles?

It is the way around the main reason why we see a lot of four-wheelers and drive four-wheeler is they don't use this tilting technology. With the carver, we have the possibility to make a very narrow vehicle. If you normally would make the four-wheel not tilting vehicle and if you take a corner too fast you will flip over to the outside. Because of this invention which we use in the Carver through the automatic tilting system it tilts like a motorbike, it drives like a car and that makes a very stable concept even when you make a corner very fast that's why we can make a vehicle less than one meter wide.
I'll start with the advantages. Personally, my biggest advantage is that so much fun to drive but that was not the reason why we developed it. We developed it because we're going to have an aero-dynamical footprint of one person wide. We specifically developed this

vehicle for one or two persons but they are sitting behind each other so there's a very less aero-dynamical drag. But then I come to the disadvantage: if you are with four persons, you should take a normal car which is suitable for four persons if you drive alone or with two, you should take this type of vehicle…yeah.

- Range anxiety in Carver users. Target customer base and reasons to pick Carver over competitors

Yes I know but as I already explained, this is a city vehicle which has top speed just below 50 kilometres an hour so if you take Carver, you take something which is in reach, drive two hours and that's a long time so you will not take Carver if you want to go from here to Amsterdam but you can take it, you'll take a Carver if you go from here to Rotterdam them so yes and no. It depends on to which kind of vehicle you compare it with. If you are four persons, you have one family you got a budget of only buying one vehicle and that people will buy four person vehicle. Specifically our target to people who are living alone or two o to be more flexible. You see a lot of people already have got a car for holidays and long distances and for cities, they use Carver.

- Design and safety?

Yeah, it's not a car, it's not a motorbike. The safety, we've got a very safe rollover cage and which protects them the person's give you the maximum protection you don't need to have and wear a helmet because all safety belts are tested. Again this is a 50-kilometer power vehicle that's a different kind of standard and if you compare it with the machines with high-speed 200 kilometres an hour vehicle so it's yeah you have to see the perspective.

- Selection of the motor in the carver and the reasoning.

We use the wheel head motor which is inside the wheel and you can see this shaft bits each on the suspension and this can turn and the rim is directly mounted on the motor. We use this kind of package because we wanted to place between the wheels our battery pack, low centre of gravity and then the wheel motors two of these, one on the left and one on the right.

1.5.4 Key vehicle specifications

Vehicle classification	
EU	L2e
Dimensions	
Length, Height, Width (incl. side mirrors)	2.89 m, 1,49m, 1.09m
Unladen & Max. permissible mass	260 kg, 500 kg

Luggage compartment	75
Number of wheels	3
Performance	
Top speed	50 km/h
Acceleration 0-45 km	8 sec
Turning circle	7.1 m
Range (WLTP)	75 km
Range (45 km/h)	100 km
Electric Motors	
Type	In wheel motor
Max power	2 x 2 kW
Max torque	2 x 150 Nm
Battery	
Battery type	Lithium Iron phosphate
Battery capacity	3.8 kWh, 60V
Charging time 100%	6.5 h
Price	
List price including 9% VAT	€ 8,990*

* Including 9% VAT, based on the insurance plate, if opting for a regular scooter licence plate, a tariff of 21% VAT applies.

To learn more about Carver, visit https://carver.earth/en

Summary

In the first lecture, we saw the main differences between Electric Vehicles (EVs) and conventional vehicles. To begin with, there are two fundamental characteristics that all cars have. The first fundamental characteristic is energy storage. The second is the motor. There are two types of motor, one is the heat engine, and the second is the electric engine. We then saw the working principle of both the type of motors. Then we looked at the advantages and disadvantages of both the motors.

The second lecture was about working on an electric vehicle. It started with a recap of why we should eliminate the usage of the internal combustion engine. Then the lecturer introduced the concept of biofuels and discussed whether it can be seen as an alternative. Finally, in the lecture, we compared the drivetrains, advantages and disadvantages of Full Electric Vehicle (FEV), Plug-in Hybrid Electric Vehicle (PHEV) and Fuel Cell Electric Vehicle (FCEV).

The third lecture dealt about major types of electric motors - induction motor, permanent magnet motor and synchronous reluctance motor. The lecturer first started with explaining classic and simple DC brushed motor. We then individually saw the working principle of all the three types of electric motors. It was followed by listing out advantages, disadvantages and real-life examples of each of them. Finally, the lecture concluded with an overview of requirements versus best suited motor for the purpose.

Practice problems

Question 1

The following exercise will be used to understand the kinetic energy and power of an electric car during braking and regeneration. For this exercise, we will assume the following parameters for three electric cars. The air resistance, rolling resistance, power conversion losses can be neglected in the exercises.

Car	*Mass*	*Battery ampere-hour*	*Persons*
EV1	*2180 kg*	*230 Ah*	*5*
EV2	*1320 kg*	*94 h*	*4*

a. *Let us consider EV 1. How much kinetic energy is stored in a car driving 50 km/h?*
   - o *210 kJ*
   - o *2100 kJ*
   - o *21 kWh*
   - o *201 MWh*

b. *The EV driver brakes the EV and iIt takes the car 10s to stop. What is the average generated power over this time interval from regenerative braking?*
   - o *2100 W*
   - o *21 kW*
   - o *3.6 MW*
   - o *3600 kW*

c. *The EV driver brakes the EV and iIt takes the car 10s to stop. What is the average generated power over this time interval from regenerative braking?*

- *0.85 C*
- *8.5 C*
- *0.11 C*
- *1.1 C*

d. *During regenerative breaking, what is the average C-rate of the battery charging when the car uses a 350 V system?*
   - *0.85 C*
   - *8.5 C*
   - *0.26 C*
   - *2.6 C*

Question 2

Consider a scenario where EV1, driving at 80 km/h, makes an emergency brake and takes 30m to come to a standstill. Where required, refer to the equations of motions to answer the below questions.

a. *How fast is the car decelerating? Assume that the car decelerates at a constant rate.*
   - *22 m/s^2*
   - *8.23 m/s^2*
   - *6.15 m/s^2*
   - *28.23 m/s^2*

b. *What is the braking force? Bear in mind Newton's law of motion.*
   - *13.45 kN*
   - *17,941.4 N*
   - *17,941 kN*
   - *13,451 N*

c. *What is the average power generated while braking? Round off to the closest value.*
   - *20 kW*
   - *200 kW*
   - *200 W*
   - *2 MW*

From the exercises above on the regenerative braking, we can see that:

- For the same nominal ampere hour capacity of the EV battery, the EV battery pack with lower voltage has a lower kWh, and hence a higher C-rate for the same (regenerative) charging power

- When an EV is braked in a short time or distance, then a lot of regenerative braking power is generated which can quite often exceed the power rating of the motor, power electronics and/or the battery. Hence, traditional friction braking has to be used in combination with regenerative braking.

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Final Quiz

Questions for Section 1.1

Question 1

Indicate if the following description belongs to a **heat engine** or an **electric motor**.

a. Burning releases the potential chemical energy in a fuel. The heat this produces causes expansion and this in turn drives some rotatory motion. ____________

b. If we place a magnetic coil between two magnets, one side of the coil will be pushed up and the other side will be pushed down. This makes the coil turn until it is vertical. At the moment we quickly change the polarity and the effect is rotatory motion.

____

Question 2

Which of the statements below about a heat engine can be seen as disadvantageous when compared to an electric engine?

a. The heat engine requires hundreds of precisely crafted moving parts.
b. Gasoline, the fuel in a heat engine, has an energy storage of 47.5 MJ/kg.
c. Efficiency of a heat engine is around 25%.
d. A lot of heat and explosions occur in a heat engine.

- statements 1, 2, 4
- statement 1, 3, 4
- statement 1, 2, 3

Question 3

Robert is planning a trip from Rotterdam, Netherlands to Antwerp, Belgium. The total distance between the two places is 110 kilometres. We saw in the lecture that 1 liter of gasoline produces 2.3 kilogram of carbon dioxide gas. Robert still decides to use a gasoline powered car for the trip. He is comforted by the fact that he has an environmentally friendly car with a mileage of 22 kilometres per liter (km/l).

What will be the amount of exhaust gas (only CO_2) in kg he produces during his trip?

Question 4

In the lecture we saw that in 2025, Lithium batteries will be weighing 200 kg to drive 500 km, whereas in 2015, for the same trip, the lithium battery was weighing 400 kg.

Ryan goes on a road trip in his electric car from Paris, France to Groningen, Netherlands. Assume it is 725 kilometres to Groningen from Paris. Choose the option that follows with the given data.

- During his trip in 2025, Ryan's electric car will have a battery that weighs 290 kg less than his trip in 2015.
- During his trip in 2025, Ryan's electric car will have a battery that weighs 390 kg.
- During his trip in 2015, Ryan's electric car had a battery that weighed 280 kg.

Questions for Section 1.2

Question 1

Here below you see comparison of total costs between Gasoline and Battery Electric Vehicle

Cost type	Gasoline	BEV 2030
Drive train	\$15k	\$5k
Battery	\$0	\$10k
Fuel	\$25k	\$8k
Maintenance	\$17k	\$6k

(BEV) 2030.

Which has a better advantage when it comes to TCO (total cost of ownership) and what is the total saving?

- BEV 2030 has a better advantage and the total saving is \$28k.
- BEV 2030 has a better advantage and the total saving is \$25k.

- Gasoline has a better advantage and the total saving is \$29k.

Question 2

Match the following statements to the vehicles that it refers to, between: **Plug-in hybrid electric vehicle**, **Full electric vehicle**, **Hybrid electric vehicle**, **Hydrogen fuel cell vehicle**.

- A vehicle has a small battery and you can replenish your range either by charging the battery from the grid or by refuelling at a gasoline station. __________________
- This type of vehicle always needs a large battery to get a long range. __________________
- This vehicle contains a small traction battery but it cannot be charged from the grid. __________________
- You can drive long distances using a fuel tank that can be quickly refuelled and only emits water vapour as exhaust. __________________

Question 3

a. Considering Figure 1.11, calculate total cost per km for ICE, BEV and HEV.

- The total cost per km for ICE, BEV and HEV is approximately \$1,00 , \$0,75 and \$1,50 respectively.
- The total cost per km for ICE, BEV and HEV is approximately \$0,70 , \$1,40 and \$1,10 respectively.

b. Choose from the options below the reason that supports the statement that a hydrogen fuel cell vehicle is not a good option when it comes to road transport.

- A hydrogen fuel cell vehicle has high infrastructure costs and vehicle costs compared to ICE and BEV .
- A hydrogen fuel cell vehicle has no battery costs compared to BEV and less energy tax compared to ICE.

Questions for Section 1.3

Question 1

Figure 1.18 shows the comparison between different types of motor. A high score means it's a better choice than the rest. Based on the figure, answer the following questions:

b. If reliability and sticker price are my main concerns, which motor should I choose?
- Induction motor
- Brushed DC motor
- Permanent magnet motor

c. If I want maximum performance in terms of size, weight and efficiency, which motor should I choose?
   - o Induction motor
   - o Brushed DC motor
   - o Permanent magnet motor

d. When I am looking at best compromise on all aspects, which motor should I choose?
   - o Induction motor
   - o Permanent magnet motor
   - o Synchronous reluctance motor

Question 2

Below you will find disadvantages of different types of motor. Match them to their respective motor type by choosing the correct options between: **inductor motor**, **permanent magnet motor**, **synchronous reluctance motor**.

1. It is not the lightest or most compact electric motor and the induced currents in the coil cause efficiency losses. ____________________
2. In this type of electric motor, there is higher inherent noise and torque ripple. ____________________
3. This electric motor needs scarce earth metal magnets and they are expensive. ____________________

Questions for Section 1.4

Question 1

Why are SiC semiconductor devices preferred over traditional Si semiconductor devices?

- o SiC semiconductor devices are cheaper than their Si counterparts.
- o SiC has a lower bandgap than Si devices and hence lower conduction losses.
- o Converters with higher switching frequency and smaller passive components can be built.

Question 2

An electric car is moving in reverse direction and the speed is continually reducing. If the x-axis indicates the Torque and the y-axis the Speed, then in which quadrant is the the operation of the electric car in the torque-speed graph?

- o Fourth quadrant
- o Second quadrant
- o Third quadrant

Question 3

The input voltage and current of a DC-DC power converter are 200V and 20A, respectively. The output voltage is 800V. Then what is the output power and output current assuming there are no losses?

- Output power=400 W, Output current=50A
- Output power=40 kW, Output current=5A
- Output power=4 kW, Output current=50A
- Output power=4 kW, Output current=5A

Question 4

What is the C-rate of an EV battery back with a nominal capacity of 100Ah and voltage of 400V and charging with a power of 80,000 W (eighty thousand watts)?

- 1C
- 0.5C
- 2C
- 2.5C

Questions for Section 1.6

Question 1

Which of the following statements corresponds to a dual motor configuration?

- *Each wheel has a separate motor to drive*
- *Two motors are used to drive the vehicle with either both motors placed on the same axle, or one motor placed in the front axle and one motor in the rear axle.*
- *The motor uses a dual (two) gear system to increase the torque.*
- *Each motor has two motor drives for controlling it.*

Question 2

Which is the most suitable electric machine technology for EVs amongst the following motors?

- *Switched reluctance motor.*
- *Stepper motor*
- *Brushed DC motor*
- *Separately excited DC motor*

Question 3

When the EV is moving in forward direction and the speed is continually reducing, the operation is in which quadrant? Consider that for the 4 quadrant operation, the speed is on the y-axis and torque is on the x-axis.

- *Fourth quadrant*
- *Second quadrant*

- *Third quadrant*

Question 4

Electric machine for EV must have ratio of peak and continuous torque:

- *Peak torque 10 times continuous torque rating*
- *Peak torque 5 times torque continuous torque rating*
- *Peak torque 2-3 times continuous torque rating.*

Question 5

In a DC motor, to control the direction of the torque of the motor, we need to control the

- *Frequency of the voltage*
- *Current direction*
- *Current magnitude*

2 Battery technology for EV

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2.0 Introduction

Electrochemical storage devices used in EV must fulfil certain requirements so that the EV can perform in a satisfactory manner. The key requirements are as follows:

- High specific energy to ensure a satisfactory range
- High specific power so that drivers acceleration expectations can be met
- Long, maintenance-free lifetime
- Safe operation under a wide range of conditions
- End of life disposal has a minimum environmental impact
- High efficiency in charge and discharge cycles.

The power and energy requirements for different types of EV's in comparison with HEV and PHEV are listed in the table below, together with common voltage ratings. For the purposes of this module five categories of EV batteries are described, which is similar to that described by Van den Bossche and Westbrook. These categories are outlined as follows:

- Lead-acid
- Nickel-based: NiMH, NiCad
- High temperature: Sodium-nickel-chloride (NaNiCl or Zebra)
- Lithium-based: Lithium-ion (Li-ion) and Lithium-polymer (Li-poly)
- Metal air: Aluminium air (Al-air) and Zinc-air (ZN-air)

2.1 EV battery introduction

Batteries can store energy and are used to power a large variety of devices, ranging from micro batteries that maintain the memory of computer chips or pacemakers up to big batteries that power electric cars and stabilize the electricity grid. Batteries that can only discharge once are called primary cells, for example, our well-known AAA and AA alkaline batteries. Batteries that can be recharged are called secondary batteries. Examples of which are lead-acid, nickel-metal hydride and lithium-ion batteries.

Batteries consist of a positive and negative pole or electrode. In a charged battery, energy is stored in a chemical form in the electrodes which is released as electrical energy when discharged. Vice versa, secondary batteries can be charged using electricity during which the electrical energy is converted to chemical energy, stored in the battery. An important characteristic of batteries is that the energy storage efficiency is very high, mostly more than 90% in Li-ion batteries.

In an electric vehicle, all the energy needed to drive is stored in the EV batteries. Moving from fossil fuel-powered cars towards battery-powered cars is challenging, first of all, because fossil fuels such as diesel and gasoline have a large gravimetric energy density compared to batteries, as shown in Figure 2.1.

Because a car needs to be as light as possible, the battery cannot be too heavy. This limits the maximum amount of energy stored in an EV battery, which itself limits the driving range. Lithium-ion batteries currently have the highest gravimetric energy density of all battery technologies. Therefore they are widely applied in electric mobility today. State-of-the-art lithium-ion batteries have an energy density close to 250 Watt-hours per kilogram, which is still relatively small compared to the energy density of fossil fuels. Gasoline, for instance, has an energy density of twelve thousand nine hundred watt-hours per kilogram. However, an electric engine is roughly 4 times as efficient as an internal combustion engine in converting chemical energy into mechanical energy. Thus an EV battery needs to be roughly 13 times as heavy as a gasoline tank to reach the same energy content.

We should distinguish gravimetric energy density from volumetric energy density. Suppose a 70 kWh battery is demanded in an EV, this results roughly in a 300 kilograms heavy battery taking a volume of approximately hundred litres. This is a limited volume hence the weight is typically the limiting factor for EV technology. A chart showing the gravimetric vs volumetric energy density for different battery technologies is given in Figure 2.2.

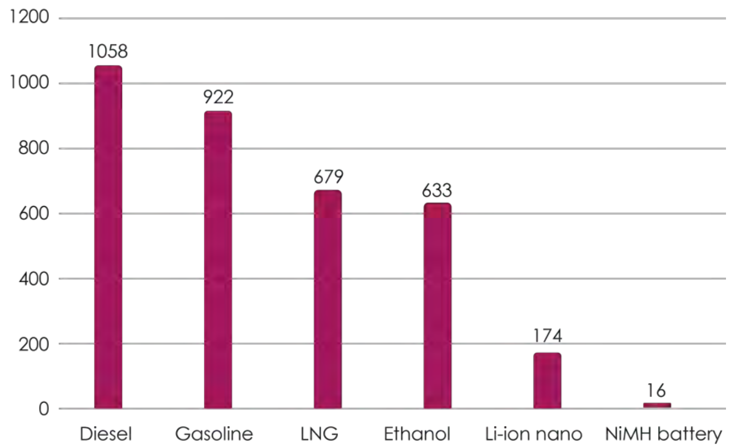


Figure 2.1 Gravimetric energy density (kWh/kg) of different storage methods

Another demand for EV batteries is fast charging, as this determines the time someone needs to spend at a recharge station to recharging the electrical car. How fast a battery can be charged or discharged is quantified by the power density, which combined with the energy density is visualized in what they call a Ragone plot, shown in Figure 2.3.

Given a demanded energy and power requirement for an EV battery, we can determine if power density or the energy density determines the weight of the battery. Suppose battery energy of 70 kWh is demanded with a required maximum power output of 50 kW, what would be the weight of the battery? This is what we can determine from the Ragone plot.

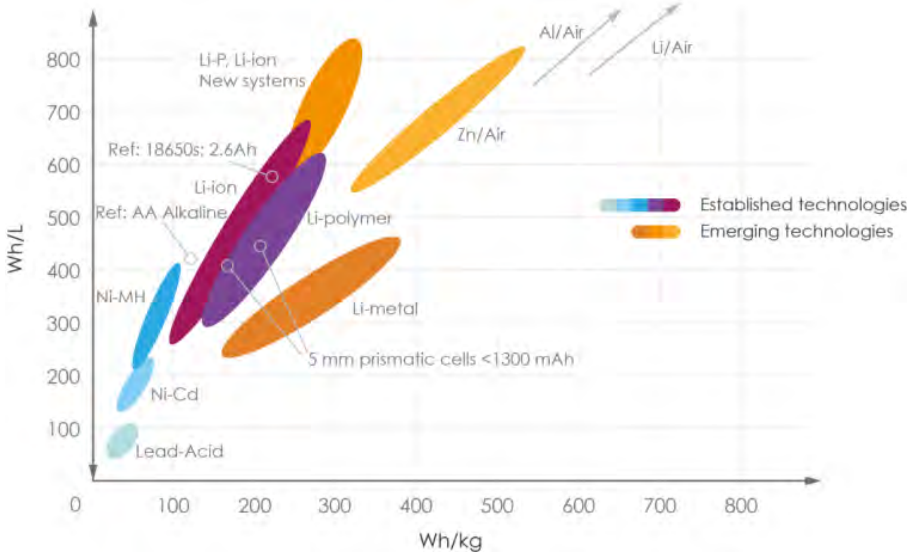


Figure 2.2 Gravimetric and volumetric energy density for different battery technologies

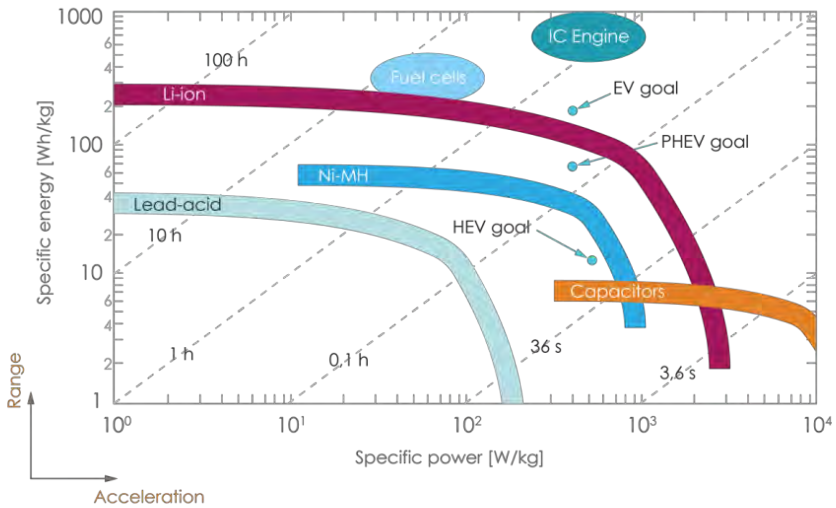


Figure 2.3 Ragone plot (Specific energy vs specific power)

Also cycle life, which is the number of cycles a battery can be recharged, is an important battery characteristic as it determines the total distance before the battery needs to be replaced. The cycle life is dependent on the operation temperature, the charge rate and the load profile.

Safety is a major concern for EV cars, and the safety specifications depend on the chemistry of the battery as its use, for instance including the charge rate and operating temperature.

In an EV, many individual cells are combined into a battery pack. For example, a Tesla car with an 85 kWh battery pack contains 7104 individual cells. A crucial component of a battery

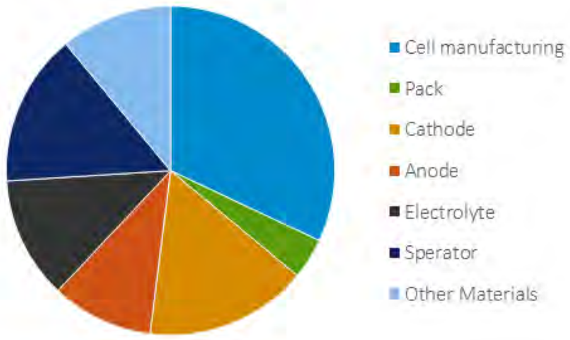


Figure 2.4 Battery cost breakdown

pack is the battery management system which monitors the state of the individual cells and manages how the individual cells are charged and discharged. This is vital to achieving safe operation, a long cycle, and optimal performance.

The two most common lithium-ion battery shapes are cylindrical and prismatic cells. Typically cylindrical lithium-ion cells are used in EV technology as they provide the longest cycle, a high safety standard and they are cheaper to produce. The disadvantage is that they are less efficient in volume packing of multiple cells, simply because of their geometry, however, for cooling of the cells, this is actually an advantage. Prismatic cells are more volume efficient, and for this reason, they are typically employed in mobile phones and tablets.

The total cost of a battery depends on the battery materials and battery production. The cost distribution depends on the specific battery chemistry and components for example here shown for one specific type of lithium-ion battery. Lithium-ion batteries have become cheaper per watt-hour of energy storage, because of scaling up production, increased energy density and cost reductions in materials for instance by reducing the amount of cobalt (Co) in a positive electrode. Recycling will become increasingly important to recover the elements and materials from lithium-ion batteries as increasing production volumes of batteries will put pressure on the price of battery materials as well as on material abundance. A cost breakdown provided in Figure 2.4.

As explained before, electric cars require batteries with a high energy density to provide a large driving range. We can see in Figure 2.5 how the price per Wh of battery storage has decreased with time, and it is expected to decrease in the future. In addition, cycle life is important to guarantee a large total driving distance before the battery needs to be replaced. Current lithium-ion technology has safety concerns which are related to the liquid electrolytes in these batteries. Battery performance and safety are determined by the materials that make up the electrode and electrolyte. Therefore, worldwide battery research and development try to find electrodes and electrolytes that improve both performance, safety and cost parameters.

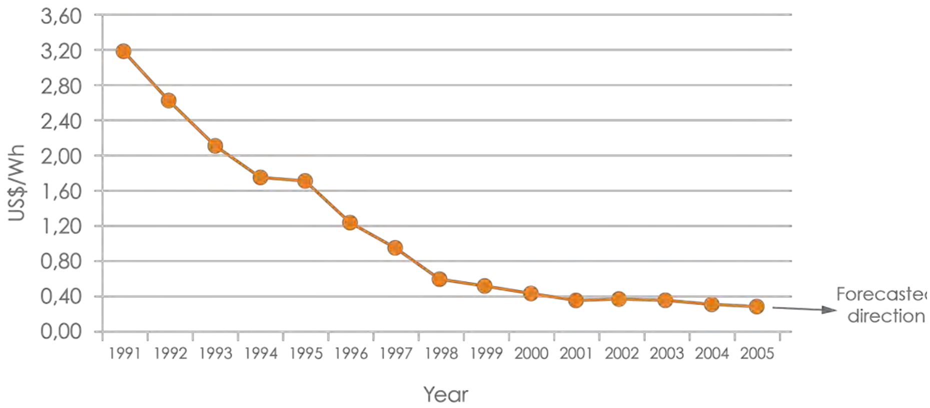


Figure 2.5 Li-ion price in $/Wh for batteries (historical trend 1991-2005)

Current lithium-ion batteries are close to the maximum theoretical energy density which is anticipated to be around 280 Wh per kilogram. New lithium chemistries are being developed to cross this limit. These new chemistries include for instance lithium-sulfide and lithium-air. At the moment, these chemistries have many challenges, in particularly their cycle life, which is related to the large structural changes and reactivity with the electrolyte.

With respect to safety, research is focusing on the development of all solid state batteries, where the liquid electrolyte is replaced by a solid electrolyte, which makes these batteries intrinsically more safe. A consideration for any lithium technology is the lithium abundance on the earth crust and the locations where it can be obtained. Lithium is relatively abundant but geographically mainly found in a few areas around the world. Also lithium is present in the oceans, but efficient lithium extraction out of seawater is not cost effective yet. Therefore also other charge-carrying ions are considered in research for EV batteries, including for instance sodium (Na) ions where one may anticipate a slightly lower energy density, based on the slightly lower battery voltages and larges sodium weight. Multivalent magnesium ions are also an interesting alternative as charge carriers, carrying two electrons per Mg-ion. Challenges of this chemistry for instance include the reactivity with the electrolyte. Intensive research is necessary to see which chemistry will be able to cross the energy density limit of Li-ion batteries.

We will now have an overview of different battery technologies for EV applications.

Lead acid batteries

This is a mature technology where limited progress has been made in terms of energy and power density. Deep cycle batteries are available, which have reenforced electrodes to avoid separation and sludge formation [1]. Prospects for use in EVs are limited, due to low energy densities, sensitivity to temperature and life cycle [2].

Nickel based batteries

Nickel-metal hydride (NiMH) batteries are used extensively for traction purposes, and are optimized for high energy content. Nickel-cadmium (NiCd) batteries also show good potential for high specific energy and specific power, although the presence of cadmium has raised some environmental concerns [3].

High temperature batteries

Sodium-nickel chloride (NaNiCl or Zebra) batteries have been deployed in numerous EV applications to date [4]. The high specific energy is attractive for long range EVs. The high operating temperature (300°C) requires pre-heating before use, which can use quite a lot of energy if parked regularly for long periods. For this reason, this battery is considered more suitable to applications where the EV is being used continuously (public transport and delivery vans etc.).

Metal air batteries

Aluminum-air (Al-air) and zinc-air (Zn-air) batteries both use oxygen absorbed from the atmosphere on discharge and expel oxygen when being charged. The energy density of these batteries is high but, lower power densities mean that applications are limited. Al-air batteries consume the aluminum electrode, and must be removed and replaced or reprocessed. Some applications have been tested where fleets of EV delivery vehicles are running with Zn-air batteries, where removable zinc cassettes can be replaced when discharged for recharged units. The low specific power of metal air batteries may see these battery types restricted to long distance delivery vehicles, but the advantages of regenerative braking may be sacrificed.

Lithium based batteries

Lithium based batteries are classified by the type of active material. Two main types exist, those with liquid (Li-ion-liquid) and those with polymer electrolyte (Li-ion polymer). The Li-on-liquid type is generally preferred for EV applications. Within the Li-ion-liquid type, there are three lithium materials, lithium cobalt, (or lithium manganese oxides), lithium iron phosphate and lithium titanate.

Lithium manganese

Lithium manganese ($LiMn_2O_4$) offers a potentially lower cost solution. It has been largely studied for electrical vehicle application, especially in Japan. The drawback of this type of battery is the poor battery life due to the slight solubility of Mn.

Lithium iron phospate

Lithium iron phosphate ($LiFePO_4$) batteries are manufactured by many companies in the world and have gained credibility through their use in power tools. Lithium iron phosphate cells have a much lower energy density than standard format cells, but can be charged much faster, around twenty to thirty minutes. Moreover, $LiFePO_4$ has been recently considered that it features an improve stability on overcharge which is good for safety, a very high power and has potential for lower cost because they use iron.

Lithium titanate

Lithium titanate allows charging on the order of ten minutes and have been shown to have an extremely long cycle life - on the order of 5000 full depth of discharge cycles. Lithium titanate has high inherent safety because the graphite anode of two other batteries is replaced with a titanium oxide.

Table 2.1 gives a final qualitative comparison of the EV battery technologies that we went through in this section [5].

Table 2.1 Qualitative comparison of EV batteries (1=poor, 2=fair, 3=good). Adapted from [9]

Attribute	Lead-acid	Ni-MH	ZEBRA	Metal-air	Li-ion
Specific energy ($kWhkg^{-1}$)	1	2	3	3	3
Specific power ($kWkg^{-1}$)	1	3	1	1	3
Capacity (kWh)	1	2	3	3	3
Discharge power (kW)	3	2	2	1	3
Charge power (kW)	1	2	2	1	3
Cold temperature performance (kW and kWh)	3	2	3	2	1
Shallow cycle life	2	3	1	1	3
Deep cycle life	1	3	1	1	2
Cost ($€kW^{-1}$ or $€kWh^{-1}$)	3	1	1	1	1
Abuse tolerance	3	3	2	2	2
Maturity technology	3	3	2	2	2
Maturity manufacturing	3	1	2	2	1
Recyclability [70]	1	1	3	2	2

Practice problems

Question 1

What characteristic determines the ability of an EV battery to be more suitable for fast charging?

- High energy density
- High power density
- Low energy density
- Low power density

Question 2

Consider the Ragone plot given in Figure 2.3. If an electric car requires 75 kWh what is the approximate Li-ion battery weight? *Hint*: Take a value of specific energy, say, 250 Wh/kg from the plot.

- 50 kg
- 150 kg
- 300 kg
- 1200 kg

Question 3

Which of the following options is a primary cell?

- Li-ion battery of your laptop
- AAA Alkaline cell
- Lead-acid battery of your car
- Capacitor

Question 4

The cycle life of a battery is dependent on:

- Operating temperature
- Charging rate
- Load profile
- All of the above

Question 5

Why are cylindrical cells preferred over prismatic cells in EV batteries?

- They have higher volumetric packing density
- They provide longer cycle life, a high safety standard and they are cheaper to produce
- They have a higher energy density
- They have a higher power density

2.2 EV battery parameters

Welcome to this lecture about EV battery performance parameters. The performance parameters of a battery are essential for safe and optimal operation. Before I will show how we can determine the performance parameters, we need to understand the basic working principle of a battery.

Every battery consists of three main components. The negative anode, the positive cathode, and the electrolyte. Other words for the electrodes are the minus pole and the plus pole. The electrolyte is typically a liquid electrolyte and together with the separator it avoids physical contact between the two electrodes. A scheme of the working principle of a Li-ion battery cell is given in Figure 2.6.

Taking Li-ion batteries as an example, when the battery is charged, lithium atoms are stored in the negative electrode but they experience a driving force to migrate towards the positive electrode. The driving force for this is chemical, which means the Li atoms prefer to be bond

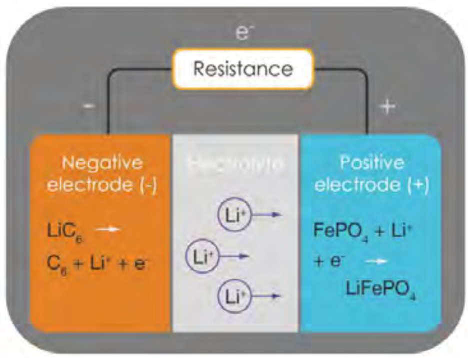


Figure 2.6 Working principle of a Li-ion battery cell

in the positive electrode material. The larger the bonding strength, the larger the potential in the electrode. And by combining an electrode with a large bonding strength towards Lithium, with an electrode with a weak bonding strength, the difference between the two potentials is made larger. This difference in potential is the battery voltage. Therefore the battery voltage represents the chemical driving force for Lithium to move from the negative towards the positive electrode. The atoms exist as ions in the electrodes, in the case of lithium as lithium-plus, keeping their electron nearby in the electronic bands of the host structure. Because the electrolyte does not conduct electrons, only the Lithium-ion can cross from one electrode through the electrolyte to the other electrode, and the electrons need to go through an external circuit, before recombining with a lithium ion in the other electrode. The electrons that travel through the external circuit generate an electrical current at this specific battery voltage. This means that the battery is effectively producing electrical energy during discharge, at least when the external circuit is closed via an application such as an EV. When all the Lithium ions from the negative electrode have reached the positive electrode the battery is fully discharged and thus empty.

The most important battery performance parameters are the capacity, state of charge, efficiency, energy content, the energy density, cycle life and C-rates. I am going to explain those one by one.

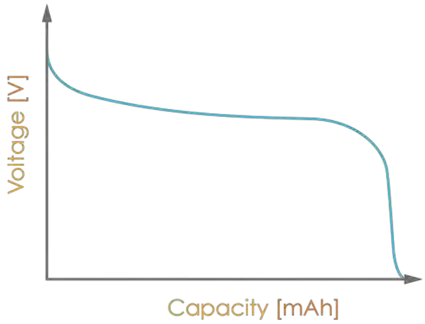


Figure 2.7 Variable voltage during discharge at constant and low current

To understand the capacity, let's look at the voltage when a Lithium-ion battery is discharged at a constant and low current. The resulting variable voltage will look like this. The voltage on average decreases during discharge because lithium ions that have the largest chemical driving force, hence the largest voltage, will go first from the negative to the positive electrode. Horizontally, in the graph in Figure 2.7, the capacity is shown. This quantifies the amount of charge that is passed during discharge from the negative to the positive electrode. It corresponds to the number of Lithium-ions, each carrying one elemental charge unit, that can be stored in the electrodes. How much lithium ions can be stored in the electrode material depends in detail on the electrode chemistry. For instance graphite can host one Lithium atom per 6 carbon (C) atoms, whereas one silicon (Si) atom can host 4.4 Lithium ions. The unit of charge is *coulomb* (C), and the elementary charge, carried by 1 electron or an ion equals 1.6×10^{-19} coulomb.

The unit of current is *ampere* (A), which corresponds to Coulombs passing per second. If we pass a discharge current during a certain time period this corresponds to a specific amount of discharge capacity. For batteries typically this is expressed in Ah, where 1 Ah corresponds to a current of 1 A during one hour, which equals 3600 coulomb.

When the battery is charged at a constant and low current, the voltage will increase, typically the same way it dropped during discharge. The voltage increases as it will get harder and harder to move the lithium ions back to the negative electrode where they are less strongly bond compared to the positive electrode. To determine how much a battery is charged in percent, we can use the State of charge (SOC). 100% represents the fully charged state. In the same way the state of discharge is defined.

The efficiency of a battery can be divided into two different types. The *coulombic efficiency* is the ratio between the discharge and charge capacity. It quantifies the ratio of electrons produced by the battery during discharge with that consumed during charge. If this deviates from 100% this implies that some charge or discharge capacity is consumed by a side reaction, were both the Lithium-ions and the electrons can be involved in these undesired side reactions. The other type of efficiency is the *energy efficiency*, that is simply the ratio of the outcoming and incoming energy.

$$\frac{\text{Discharge capacity}}{\text{Charge capacity}} = \text{Coulombic Efficiency} \tag{2.1}$$

$$\frac{\text{Energy out}}{\text{Energy in}} = \text{Energy Efficiency} \tag{2.2}$$

The total amount of energy stored in the battery during charge, and released during discharge corresponds to the average voltage times the capacity. This corresponds to the area underneath the discharge or charge plot. Multiplying the unit of voltage, *volt*, with the unit of capacity, *coulomb*, leads to the unit of energy, *joules* (J). Figure 2.8 shows the charge-discharge voltage versus capacity, this means that the area underneath the voltage curve represents the energy consumed during charge, and produced during discharge. Because the capacity is typically expressed in ampere-hours, multiplication with the voltage results in watt-hour (Wh), which is the unit most often used to express the energy content of a battery as we have seen before. For the conversion to joules you need to realize that 1 watt-hour is the same as 3600 J.

The energy density is another very important parameter. There are two types of energy density, one is per weight and one is per volume. Now that we know how to determine the energy that can be stored in a battery, we can obtain the gravimetric energy density by dividing the energy content by the battery weight resulting in the unit watt-hours per kilogram. The energy density per volume is called the *volumetric energy density*. To obtain the volumetric energy density we divide the energy by the volume of the battery, typically in Liters. The gravimetric energy density is most relevant for EVs, and the volumetric energy density for portable electronics.

We need to make a distinction between the energy that is stored during charge and the energy that we get out during use of the battery. The ratio of these two is the energy efficiency of the battery. The energy efficiency of most batteries is relatively large compared to other energy storage technologies, typically above 90% for Li-ion batteries. However, as we will see later the energy efficiency depends on how fast we charge and discharge.

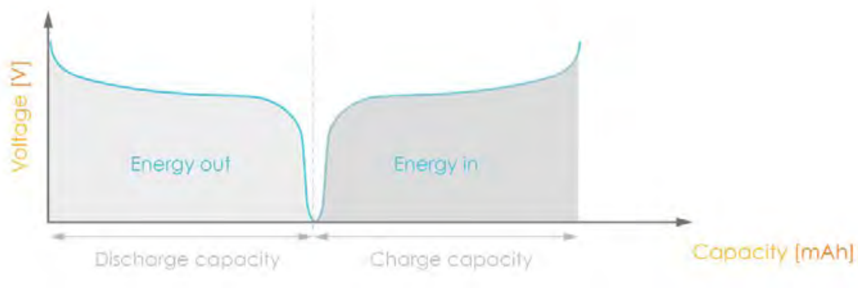


Figure 2.8 Voltage-capacity characteristic at charging and discharging

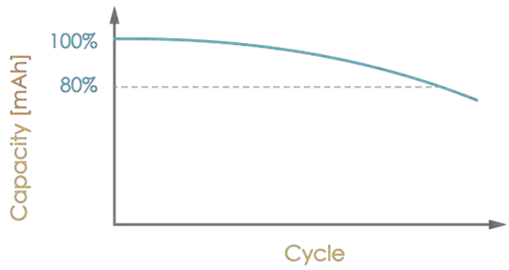


Figure 2.9 Capacity decreases with the number of charging-discharging cycles

Upon repeated charging and discharging, a battery loses some capacity, as shown in Figure 2.9. This is called capacity fading and is the main reason why batteries have a so called *cycle life*. When 80% of the starting capacity is left, the battery is often considered to be at the end of its cycle life, at least for EV applications. In the next section we will discover what origin is of capacity fading.

Up to now we assumed small charging and discharging currents. When the currents are larger, the observed battery capacity will change. Before looking into this we have to quantify the charge rate.

With the current we can control the charge or discharge rate and therefore how fast a battery is charged or discharged. Because the total charge or discharge time will depend on both the current and the battery capacity, the charge or discharge rate is often is expressed in C-rate, which takes into account the capacity of the battery.

The C-rate, or X-rate, represents the current to charge or discharge the battery to its full capacity in X hours. For instance C/20 corresponds to the current that would charge or discharge the battery in 20 hours, 10C corresponds to the current that would charge or discharge the battery in 0.1 hours, which is 6 minutes. It is thus clear that higher C-rates will lead to higher charging currents. Unfortunately, higher C-rates come with a price, namely lower efficiency.

Another unit frequently used is the specific current, the current normalized per gram of active electrode material. Let's have a look at how a typical charge and discharge curve schematically looks at different charge rates expressed as C-rates.

The voltage during charge increases when we apply larger currents, and it decreases during discharge. This is the consequence of the internal resistance of the battery. For very small currents, like C/20, the voltage is typically close the chemical driving force, whereas at large currents it will deviate the current times the internal resistance. This voltage deviation is referred to as the over potential. Note that the current *I*, is negative during discharge and therefore is the over-potential is negative during discharge.

The dependence of the charge and discharge voltage on the current also has consequences for the capacity. This is because both charge and discharge capacities are restricted by the so called a cutoff voltages V_{min} and V_{max}. This is to protect the electrode and electrolyte materials to degrade, which typically results in a shorter cycle life and lower energy efficiency, which will be discussed in the next lecture.

Because the voltage during charge increases when we apply larger currents, the high voltage cutoff is reached at a smaller charge capacity compared to lower currents, as shown in Figure 2.10. Similarly, because the battery voltage drops during discharge with increasing currents the low cutoff voltage is reached at a smaller discharge capacity. As a consequence, the energy efficiency goes down (see Figure 2.11) with increasing charge and discharge currents. More energy is lost at high currents, as a direct consequence of the internal resistance. A larger internal resistance leads to larger energy losses, which are dispersed as heat in the battery.

How the energy density depends on the current rate for a specific battery, is quantified by the power density, which is the rate with which the energy can be inserted or extracted per unit time per weight expressed in W/kg. Looking at the Ragone plot, you see that higher specific power leads to lower specific energy. Therefore, you could argue there is a very important trade-off to be made between energy and power.

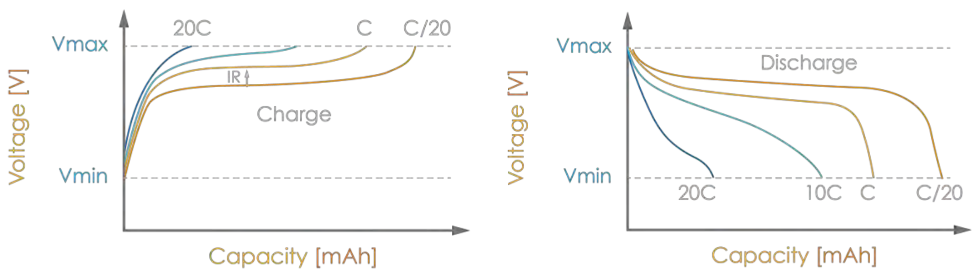


Figure 2.10 Effects of C-rate on charging and discharging voltages

Let us now define the **specific power limitation**. This is 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 [6]. 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.

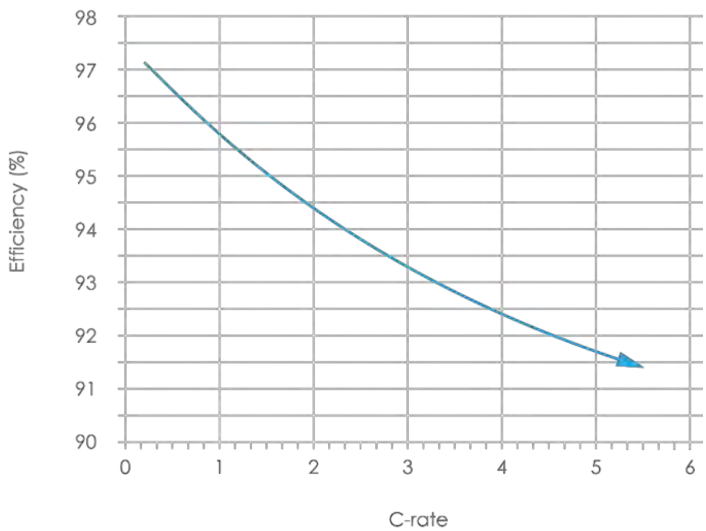
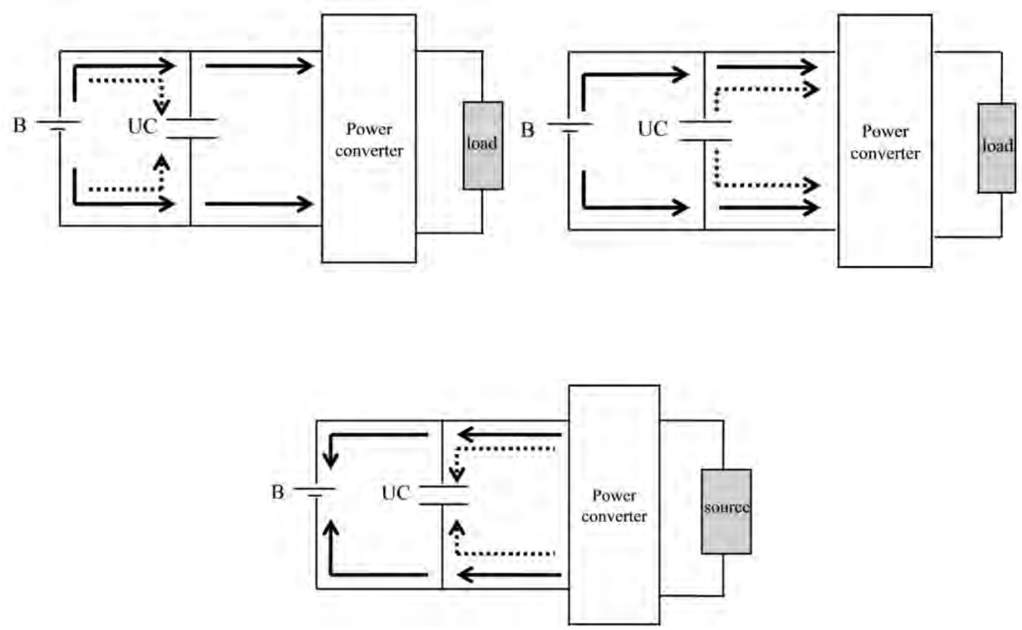


Figure 2.11 Effect of C-rate on battery efficiency

recharged using regenerative braking



The **specific energy limitation**, i.e. 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 9.2 kWh/kg corresponding to more than 3 kWh/kg 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).

One method of achieving electrical energy storage with a high specific power is to use ultracapacitors (UC) in an **hybrid energy storage** setting [7]. 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 Figure 2.12. This type of set up combines the high specific power density of UC's with the higher specific energy of an electrochemical battery (B). 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.

Another important aspect that needs to be taken into account is **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 [EPA], is shown in Table 2.2.

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.

Now we established the most important parameters that describe battery performance and how they depend on each other. In the next lecture we look inside the battery in more detail, how these battery performance parameters depend on the battery chemistry inside.

Practice problems

Question 1

Using the Ragone plot, and based on the energy density, what would be the weight of the battery if it's a lead-acid battery? Assume for this question that the specific power of both

Table 2.2 EPA testing cycle attribute of EVs. Adapted from [EPA]

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

the batteries are 10W/kg.
And, if it’s a Li-ion battery?

Question 2

Using the Ragone plot, and based on the power density, what would be the weight of the battery if it’s a lead-acid battery? Assume for this question that the specific energy of both the batteries are 10Wh/kg.
And, if it’s a Li-ion battery?

Question 3

The EV battery rated for 75 kWh and 50kW is now built using the lead acid and Li-ion battery technology, respectively. How long does it take to charge the Lead-Acid battery at the rated power?
And, the Li-ion battery?

Question 4

Now, suppose in the future batteries can be charged in 10 seconds. Assume a battery cell voltage of 3.6V and 100 cells are connected in series in the battery pack of 75kWh. What is the power required?
What is the corresponding current at the battery pack level ?

Question 5

What are the practical implications of Question 4?

- None
- Powerful active cooling
- Massive cables/connectors
- Powerful active cooling and massive cables/connectors

Question 6

In case of a low power demand from the vehicle in case of hybrid energy storage

- Battery delivers the power and is simultaneously charging the ultracapacitor.
- Both battery and ultracapacitor contribute to the total power supply.
- Only ultracapacitor delivers the power.

2.3 Processes and materials inside the battery

Let's consider the atomic scale working of a Li-ion battery by looking at the classical combination of a graphite negative electrode with a Lithium cobalt oxide or LCO positive electrode, as commercialized in 1991.

Lithium can be stored between the graphene layers in graphite, and in the interlayers of the cobalt oxide host. Lithium is relatively weakly bonded in graphite (the negative electrode) compared to in LCO (the positive electrode). The resulting chemical driving force for lithium to move from the graphite towards the LCO expresses itself as battery voltage. This driving force will cause the battery to discharge spontaneously, but only if the Li-ions are allowed to move through the electrolyte from the negative to the positive electrode.

As we can see from Figure 2.13, the electrolyte only allows passage of Li-ions, positively charged Li. Therefore, discharging requires the electrons to go through the external circuit. Only when the external circuit is closed, via an application, an electrical current will run, driven by the Li-ions that migrate from the negative to the positive electrode. Under these conditions the battery is discharging.

During discharge the negative electrode produces electrons, corresponding to oxid**A**tion of the graphite, in which case the negative electrode is called **A**node. At the positive electrode, electrons are consumed, which corresponds to redu**C**tion of the LCO, in which case the positive electrode is called **C**athode.

Charging the battery is achieved by applying a current opposite to discharging, which requires a voltage larger than the battery open circuit voltage. This will drive the electrons back from the positive to the negative electrode via the external circuit and thereby also the Li-ions. In this case electron production and consumption are reversed, and thus also the anode-cathode assignment switches between discharge and charge, as opposed to the negative/positive electrode assignment that remains the same.

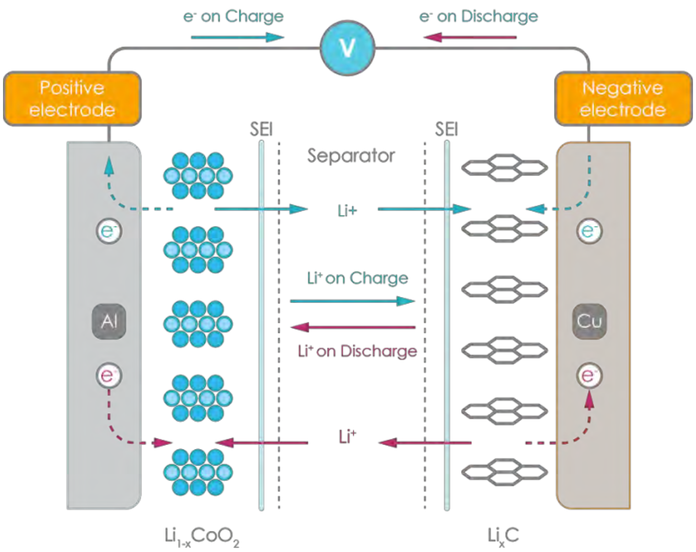


Figure 2.13 Li-ion battery process at the atomic scale

Now we are going relate the atomic scale properties of electrode materials to the macroscopic performance parameters. Let's start with capacity, voltage and energy density. The chemical reactions that occur in batteries involve electron transfer, which are called redox reactions referring to reduction and oxidation. From the battery redox reactions we can calculate the capacities of the electrodes, which you can practice during exercises after this lecture. Here you see the redox reactions at both electrodes, which to the right represent discharging of the battery. These are called insertion reactions because the lithium ions are inserted into a host material at the negative and positive electrode, as the battery charges and discharges, respectively.

$$\begin{aligned} &(+)\ \ Li_{0.5}CoO_2 + 0.5Li^+ + 0.5e^- \leftrightarrow LiCoO_2 \\ &(-)\ \ LiC_6 \leftrightarrow 6C + Li^+ + e^- \end{aligned} \tag{2.3}$$

The approach of calculating the electrode capacities and the battery energy density is as follows: Imagine we need to store 1 mole of Li-ions, then the capacity equals Faraday's constant: 96500 Coulomb. To store this capacity in the Li-ion battery we can determine the amount of moles of electrode materials from the redox reactions and from this there mass of the electrodes. The capacity divided by the weight of the electrode is the specific capacity. Because the anode and cathode generally have a different specific capacity, the masses of the anode and cathode will be different. Remember that energy density is given by:

$$\text{Theoretical energy density} = \frac{(\text{Capacity} \cdot \text{Average voltage})}{\text{Weight electrode materials}} \tag{2.4}$$

Therefore, the theoretical energy density of the combination of the two electrodes equals the capacity times the average voltage divided by the total mass of the two electrode materials. The practical energy density of the entire battery is much smaller, roughly around 30% of the theoretical energy density, because of the weight of the non-active materials including the electrolyte, current collectors and packaging. Both the specific capacities and average potentials of existing electrode materials are known, making it possible to calculate the energy density of any combination of electrodes, as depicted in Figure 2.14. The potential of electrode materials is typically referenced to that of Li-metal. The Li-metal potential is conveniently set to 0 as reference potential, which has no consequence because the battery voltage is always a difference between electrode potentials.

The internal resistance and power density determine, for instance, the charging time of batteries. As a result of the battery internal resistance, the battery voltage increases with the charge current, and decreases with the discharge current as we have seen in the previous lecture. As a consequence the energy efficiency reduces with increasing current, and as a consequence more heat is produced in the battery.

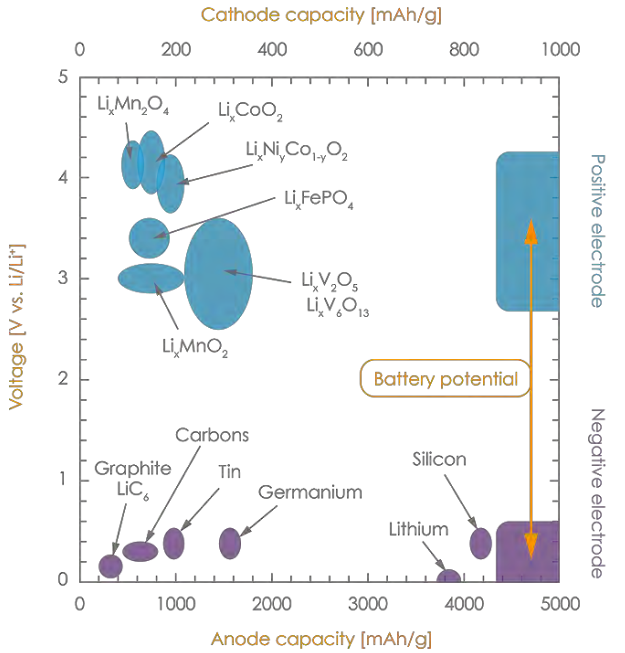


Figure 2.14 Energy density by the potential difference of the chosen electrodes

Looking into batteries in Figure 2.15 there are four main contributions to the internal resistance:

(1) Li-ion conduction through the electrolyte,

(2) charge transfer of the Li-ions towards or from the electrode material,

(3) Li-ion conduction through the electrode material and finally

(4) electron conductivity between the electrode material and the current collector.

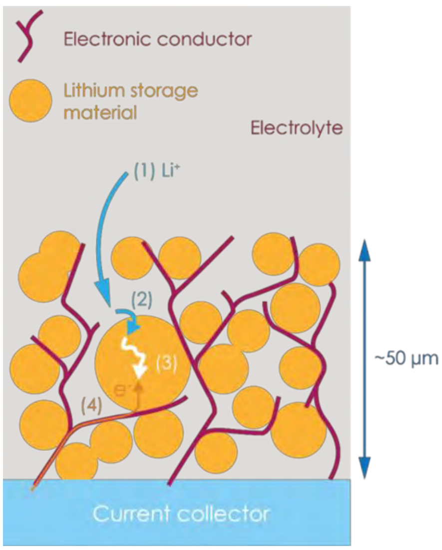


Figure 2.15 Charge transport and internal resistance

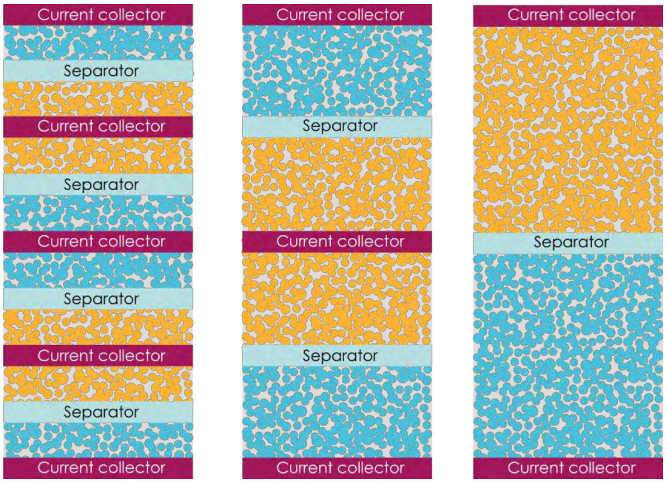


Figure 2.16 Trade-off: Energy density vs Power density

In many cases Li-ion transport through the electrolyte in the pores of the electrodes dominates the internal resistance, and therefore it determines the dis(charge) time and the power density. A way to improve the Li-ion transport through the electrolyte that fills the pores of the electrode, is to make electrodes more porous (see Figure 2.16 and 2.17).

However, that decreases the amount of electrode material, which lowers the specific capacity of the electrode. This effectively lowers the battery energy density as the same weight of current collectors, separator and packaging are required. Another strategy is to make electrodes thinner, but also that results in less electrode material, and hence in a lower energy density. Effectively both strategies will increase the power density, leading to shorter charging times, but at the expense of energy density, demonstrating the trade-off between power density and energy density.

As a consequence a Li-ion battery designed to have a high power density will have thinner electrodes as compared to that designed for high energy density. On the left we see a high power density battery, and on the right we see a high energy density cell.

Next, we consider potential causes of the finite cycle life of batteries, which translates into the limited amount of times they can be charged and discharged. The electrolyte in a battery is exposed to the reduction and oxidation potentials of the two electrodes. If the electrolyte is oxidized or reduced by these potentials this implies that the electrolyte is decomposed into other species, which may be insoluble in the electrolyte often bonding Li in such a way that it

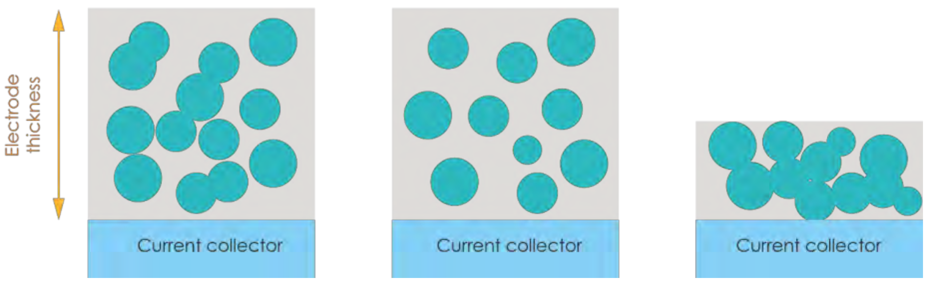


Figure 2.17 Electrode thickness and porosity determine power and energy density. From left to right: regular electrode, porous electrode and thin electrode

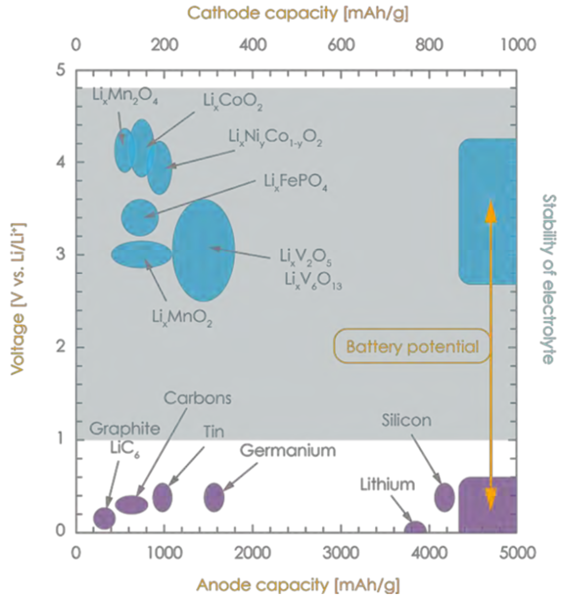


Figure 2.18 Cycle life: Electrolyte stability

is not active anymore. As a consequence some capacity is irreversibly lost and part of the electrolyte is decomposed, which are major factors that cause a finite battery cycle life.

For the large voltage of lithium ion batteries, stable organic electrolyte have been developed. By mapping the electrolyte stability window on the potentials of the electrodes, we can determine which electrodes fall within the electrolyte stability window. However, it is not always necessary to have electrode potentials within the stability window to achieve a long cycle life. Looking at graphite, the potential is below what existing electrolytes allow, hence the graphite negative electrode will reduce the electrolyte. Nevertheless, graphite is the most applied negative electrode in Li-ion batteries. How does this work? Depending on the electrolyte, its reduction leads to solid electrolyte decomposition products on top of the graphite surface. This film is known as the solid electrolyte interphase, or SEI and it shown in Figure 2.19.

The SEI should not conduct electrons to protect the rest of the electrolyte from the graphite electrode potential. In that case electrolyte decomposition is passivated, similar to a thin

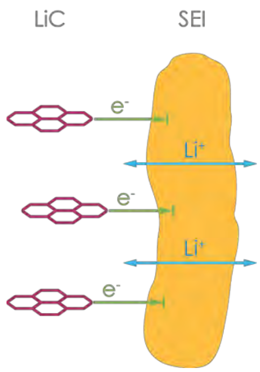


Figure 2.19 Solid Electrolyte Interphase (SEI)

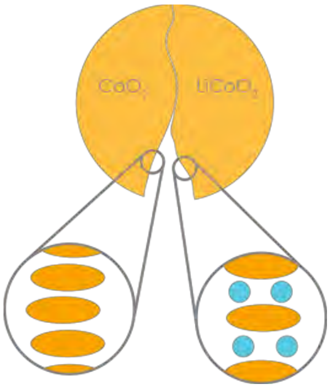


Figure 2.20 Cycle life: volumetric changes leading to cracks and capacity loss

aluminium oxygen layer that prevents Al to oxidize further when exposed to air. The SEI should conduct Li-ions, allowing the necessary Li-ion transport during battery charge and conducting SEI aiming at a long battery cycle life [8].

Another aspect that can lower the cycle life of Li-ion batteries is the repeated volume changes of the electrodes upon Li insertion and extraction during battery cycling. During cycling this may result in cracks in the electrode material, as portrayed in Figure 2.20. As a consequence the electrode material may become isolated from the current collector, and thereby inactive, resulting in capacity loss over cycling. Depending on the specific electrode material, large structural changes typically play an important role in the cycle life of Li-ion batteries. Hence, the battery lifetime depends on the depth of discharge (DOD), the number of cycles and the age [9].

The state of health (SOH) of a battery system is a term used to describe the energy content of the battery after consideration of aging effects. In terms of EV performance, relating the State of Charge (SOC) to the SOH provides a more accurate indication of the energy remaining in the battery and thus a more accurate fuel gauge to the driver. This concept is explained with reference to Table 2.3. Assuming an energy usage of 0.2kWh/km and a battery with a capacity of 30kWh, a range of 150km is achieved. However as the battery ages and the capacity decreases, the range decreases. If the battery energy indicator does not consider this aging effects, the EV will have a shorter range than predicted.

Also the operation conditions of Li-ion batteries have a large impact on the battery cycle life, as graphically shown in Figure 2.21. High temperatures enhance electrolyte decomposition, which as discussed, is detrimental for the cycle life. High temperatures can occur due to the outside temperature, but also because of heat development in the battery due to the internal

Table 2.3 Effect of battery age on SOH

Age	SOH (% of capacity)	Range (km)
Beginning of life (BOL)	100	150
Middle of life (MOL)	90	135
End of life (EOL)	80	120

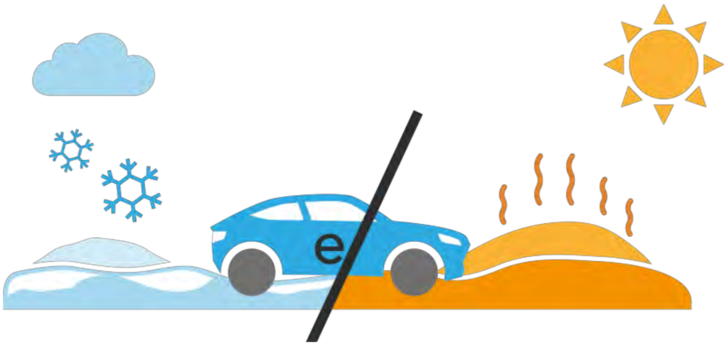


Figure 2.21 Weather and temperature effect on the battery performance and life cycle

resistance. This may require active cooling to guarantee a longer cycle life. Low temperatures increase the internal resistance, which effectively lowers the power and energy density of batteries, but only when kept at a low temperature.

Batteries for electric vehicles consist of many interconnected cells in combination forming a battery pack. Individual battery cells a show a reduction in capacity with increasing charge and discharge cycles, as well as variations in temperature. When cells are connected in a series or parallel configuration as in a battery pack, management and control of the charge and discharge conditions becomes crucial to extend the lifetime and limit ageing effects of individual cells. A battery management system (BMS) is used to monitor, control and balance the pack. The main functions of a BMS are outlined in the figure below. Without balancing the battery pack, the battery is not only risking unnecessary damage, it is also operating sub-optimally. Because the worst cell is limiting the performance of all cells in the battery pack, it is very important to prevent big differences in cell's state of charge.

The cost and complexity of a BMS depends on the functionality and intelligence built into the management system. State-of-charge (SOC) estimation is an important parameter to measure accurately, especially if EV's are integrated with a smart electrical grid. Different methods of estimating SOC are detailed in [10]. An overview of a BMS scheme is provided in Figure 2.22.

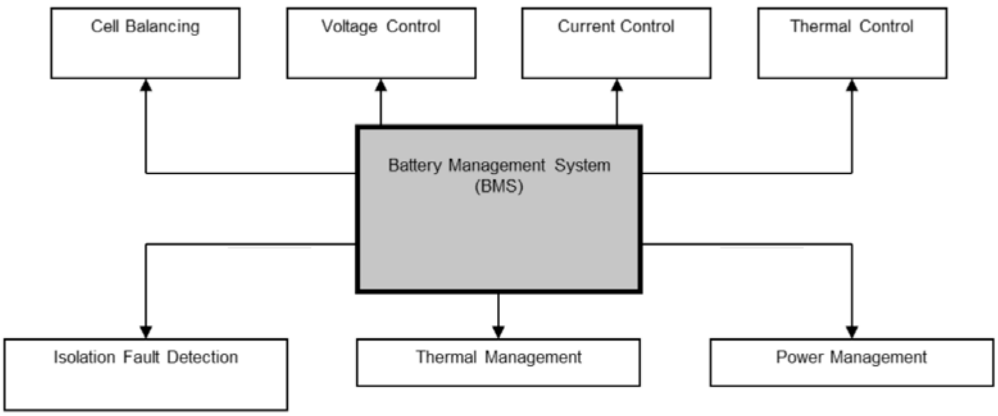


Figure 2.22 BMS structure scheme

Because the performance of battery cells varies with temperature, it is therefore crucial to include a thermal management system in the battery pack. This ensures all cells are both electrically and thermally balanced and the lifetime will be extended. Thermal management systems can either use air or liquid as the transfer medium. For integrating into the vehicle, the power consumption must be low and it must not add much additional mass. The thermal management system can realize its performance requirements using either passive or active means. A passive system using only the ambient environment may provide sufficient thermal control for some battery packs whereas active control may be required for others.

To understand the importance of the battery management system, we take a closer look inside. The BMS has the possibility to monitor and control (directly or indirectly) several different parameters of the battery:

- Voltage
- Current
- State of charge
- Temperature
- State of health

First of all, the voltage of the total battery pack and of the individual cells are monitored by the BMS. The BMS can keep track of the difference between the minimum and the maximum cell voltages, and estimate if there is a dangerous imbalance in the battery pack. The charging and discharging current of the battery pack is essential to control, as too high current can overheat a battery and lead to a failure. Further, improper control of the charging and discharging current can lead to overvoltage and undervoltage of the battery, respectively that can harm the battery on the long run.

The state of charge function is extremely important to keep track on, because many batteries must not be discharged below a certain percentage. This is because, if the depth of the discharge becomes too high, some batteries can start to break down or lose their capacity. The state of charge can be determined from the measured values of the voltages and currents.

Another function is the temperature of the battery pack and the individual cells. Temperature is directly related to the battery lifetime, as high temperatures can degrade the battery faster. The individual cell temperature is important to know as well, to see if there are local hot spots, indicating a possible failure. Using the BMS together with the battery thermal management system can cool the battery and keep it within a nominal range. When there is a coolant available, the temperature of the intake and output coolant temperature is an important indicator of the temperature of the battery pack.

The state of health is a measurement to estimate the overall condition of the battery with respect to lifetime. Battery cell balancing is a key feature of the BMS to help increase battery life. Naturally, after a while, the different cells in a battery pack will start to show differences in the state of charge and thus show localized under or overcharging. This can have multiple causes. For example manufacturing inconsistencies, different charging/discharging currents, heat exposure and more. This is detrimental to the lifetime of the battery pack because most cells in the battery pack are connected in series (adding voltages). This means that if one battery cell breaks down, the whole battery pack will seem to be broken (zero current). The BMS can perform balancing in a passive or active way. In the case of passive cell balancing, passive elements such as resistors are used. This is simple but inefficient as it leads to power losses in the resistors. On the other hand, in case of active balancing, DC-DC power electronic converters are used to equalize the cells and reduce the differences between the operational state of individual cells.

Almost all electric vehicle battery systems are made with the lithium-ion battery chemistry. Lithium-ion rechargeable batteries are more sensitive to imbalance than other battery chemistries. This is because lithium battery chemistries are more susceptible to chemical damage, like cathode fouling, molecular breakdown and unwanted chemicals from side reactions. The chemical damages will occur quickly in lithium-ion batteries when slight overvoltages or overcurrents are applied. Heat accumulation inside the battery pack can accelerate these unwanted chemical reactions.

Lithium battery chemistries often permit flexible membrane structures, which makes it possible to use lightweight sealed bags, improving the energy density and specific energy of the battery. Some unwanted chemical reactions that occur when the battery is mistreated, will result in gaseous by-products. This leads the batteries to become ‘puffy’ or ‘balloon-like’, which is a strong indicator of a failed battery. The big danger in lithium-ion batteries is the accumulation of pressure, which can lead to an explosion. The organic electrolyte contains hydrocarbon chemicals which are flammable, leading to a dangerous cocktail upon battery failure. This illustrates why a proper battery management system is crucial for lithium-ion batteries.

It is clear that the BMS, through balancing, thermal management and control of voltage and current helps in improving the battery life. Another important factor that can improve battery life is to reduce the number of charge-discharge cycles and the maximum depth of discharge. The battery should not be completely charged and discharged, because this is detrimental to battery life. Furthermore, some EV manufacturers let their customers set the maximum percentage until which the battery should be filled for every-day use, and they recommend a rather low setting of around 80%, which can be increased for longer trips.

Another setting in EVs which is sometimes available is the option to limit the power output of the car. This has the downside of having lower acceleration, but it limits the discharge rate of the battery and therefore is less detrimental to the battery.

Practice problems

Question 1

Which factor(s) determine the internal resistance of a Li-ion battery?

- Li-ion conduction through the electrolyte.
- Charge transfer of the Li-ions towards or from the electrode material.
- Li-ion conduction through the electrode material.
- Electron conductivity between the electrode material and the current collector.
- All of the above.

Question 2

Consider the following two statements.

A. The electrode at which oxidation takes place is the anode. During discharge, this is the negative electrode.
B. The electrode at which reduction takes place is the cathode. During discharge, this is the positive electrode.

- o Only statement A is true.
- o Only statement B is true.
- o Both statements are true.
- o Both statements are false.

Question 3

The cycle life of a Li-ion battery is dependent on

- o Electrolyte stability
- o Operating conditions
- o Structural changes in electrode due to Li addition
- o All of the above

Question 4

Consider the following two statements.

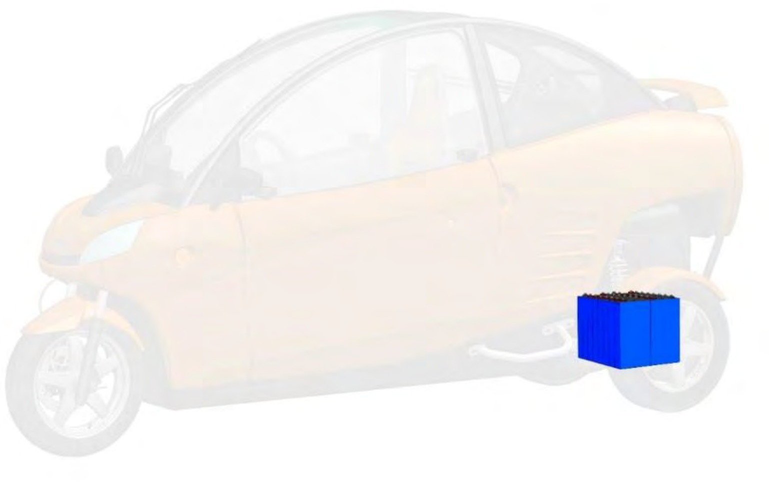
A. The main role of the BMS is to balance the state of charge of the individual cells.
B. This is done to prevent individual cells to be at a relatively high or low state of charge, which exposes the electrolyte to relatively large overpotentials. This in turn may lead to electrolyte degradation and hence reduced battery life.

- o Only statement A is true.
- o Only statement B is true.
- o Both statements are true.
- o Both statements are false.

2.4 Case study: Carver

Carver electric vehicle uses 5.4kWh Lithium iron phosphate battery. The charging time is 4.2 hours to 80%, and 6.5 hours to 100%.

The battery, along with the battery management system, is located in the back of the car, between 2 wheels:



In this video, Chris will tell us about the type of battery they used and why they choose it, their methods to ensure battery longevity, and charging methods of Carver electric vehicles.

- Ideal battery for an EV

Well the one that is cheap and has a lot of life cycles will be an ideal battery.

- Reasons for Li-Ion batteries and the type of cells

We use Li-Phosphor cells. We use 16 of these. Basically we chose this type of battery because basically, this is very reliable and safe, so it does not get punctured and catch fire which very important issue because we want this to be as safe as possible. Secondly and these kinds of cells were very easy to package, 16 so two rows of 8 cells in combination with our own battery management system on top of it. So this is why we chose this kind of battery. They are cube wise so you can easily pack them.

- Carver's strategy to ensure battery longevity

We do both. We definitely dump, and not take out 100% of the battery and we keep a big amount, we use less than maximum capacity. First of all, to ensure the lifecycle is, it's good for the lifecycle. Second, as the battery is getting old, the maximum amount of energy starts getting less and less and less. So we start already with less, then battery capacity is getting less, the range capacity will not kick in, because we cover certain amount over in the beginning. So then a customer thinks, "Okay, I can always drive to work" and even when the car could be three years old, he can still have exactly the same range, and not in the beginning too much and when the battery is getting older, the range is getting less and less and less.

we don't need because our battery is capable of pulling out much more than what we

- Cooling of batteries in Carver

are doing and it also has to do with our legislation of the vehicle and we are only

allowed to take two kilowatts of the motor. So we don't need to cool the batteries.

- What are possible battery chemistries being considered for future EVs and why ?

We keep our eyes open. It's always a combination of prices the availability, because not everybody is willing to deliver your batteries and how it's easily packaged in the vehicle. So a lot of reasons why we choose a specific type of the battery.

- Technological challenges when moving from a single cell to a EV battery pack ?

That's a good question single-cell quite simple because you charge me so you know which kind of cut off voltage you have to get out. With lithium cells different than, with the lead acid batteries when you charge them and they have the tendency that the voltage of all both the cells getting higher or lower with old school lead, the efficiency and the charging but they all end up having the same State of Charge. With Lithium, you have to be careful and that's why you have to use a battery management system, which measures the voltage of every cell individually, and take a look at them. See, "that one is too full, so we have to empty that one a little bit. That one is bit too empty, so we have to charge that one up".

- How long does it take to charge the battery, ways to reduce the charging time, lifecycle of the battery and maintenance needed.

Around four and a half five hours. Yeah, we with the Carver we don't have that quick charge so we have no DC charging. We wanted to make it as simple as possible it's this just like vacuum cleaner you can put it into any socket. So if you want to increase the charging speed, or decrease the charging time we have to introduce the DC charger. It is at the moment 4000 cycles and that's a long time and that's what our manufacturer and supplier is guaranteeing us. But we have not reached that point at this moment you as you calculate four thousand times…it's 4,000 days of riding.

Summary

Let us now summarize the main learnings from this module on Battery Technologies for EVs. In addition, we have prepared some exercises which would help you revise some of the important concepts you learned this week.

So, we learnt that Electrochemical storage devices used in EV must fulfil certain requirements so that the EV can perform in a satisfactory manner. The key requirements are as follows:

- High specific energy to ensure a satisfactory range
- High specific power so that drivers acceleration expectations can be met
- Long, maintenance free lifetime
- Safe operation under a wide range of conditions
- End of life disposal has a minimum environmental impact
- High efficiency in charge and discharge cycles.

  Furthermore, we learnt:
- To interpret Ragone plots
- To calculate the energy content and capacity of batteries
- Atomic-scale working of batteries About the trade-off between energy density and power density in designing batteries
- About factors which determine the battery life of EVs
- About the significance of the Battery Management System
- About the application of Buck/Boost converters to step down/ step-up voltage for power transfer between battery and motor in EVs

Practice problems

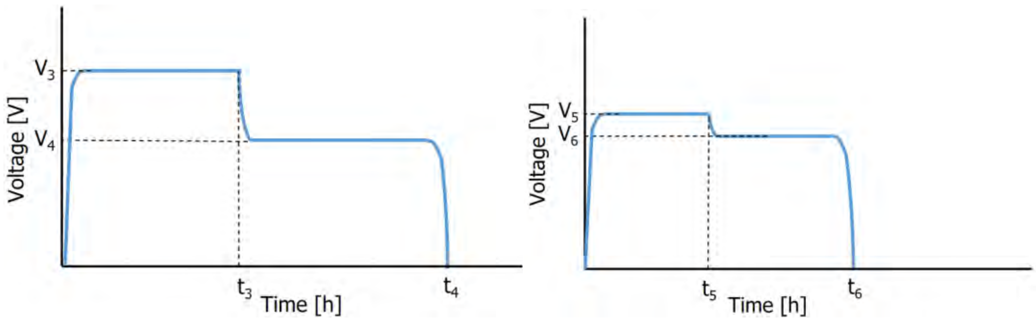
Question 1

Two batteries are galvano-statically tested (constant current, 6 A) to determine their electronic performances. The first charge/discharge cycle is the same for both batteries. Mass of a single battery = 0.2 kg.

After 250 cycles the following voltage profiles belong to battery 1 (Figure 1) and 2 (Figure 2)

V_3 = 3.3 V, V_4 = 2.6 V, t_3 = 10h, t_4 = 18 h

V_5 = 3.0 V, V_6 = 2.8 V, t_5 = 8 h, t_6 = 15 h



Voltage profile battery 1 Voltage profile battery 2

a. Calculate the specific (discharge) capacities of battery 1 & 2 (in mAh/g)
  - Battery 1 → 140 mAh/g & battery 2 → 110 mAh/g
  - Battery 1 → 240 mAh/g & battery 2 → 210 mAh/g
  - Battery 1 → 340 mAh/g & battery 2 → 210 mAh/g
  - Battery 1 → 240 mAh/g & battery 2 → 310 mAh/g

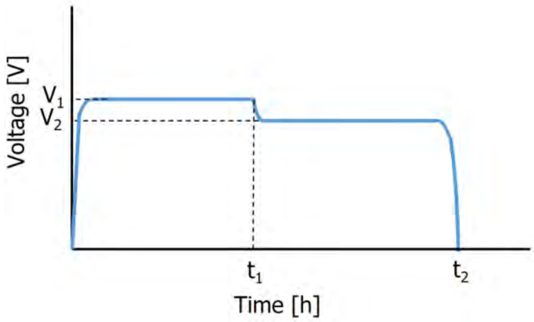
b. Calculate the specific energy densities of batteries 1 & 2 (in Wh/kg)
  - Battery 1 → 684 Wh/kg & battery 2 → 488 Wh/kg
  - Battery 1 → 684 Wh/kg & battery 2 → 448 Wh/kg
  - Battery 1 → 524 Wh/kg & battery 2 → 488 Wh/kg
  - Battery 1 → 624 Wh/kg & battery 2 → 588 Wh/kg

c. Calculate the Coulombic efficiencies of the batteries 1 & 2
  - Battery 1 → 80% & battery 2 → 87.5%
  - Battery 1 → 82.5% & battery 2 → 87.5%
  - Battery 1 → 80% & battery 2 → 92.5%
  - Battery 1 → 82.5% & battery 2 → 92.5%

d. Calculate the energy efficiencies of the batteries 1 & 2

- o Battery 1 → 33% & battery 2 → 63%
- o Battery 1 → 63% & battery 2 → 82%
- o Battery 1 → 53% & battery 2 → 92%
- o Battery 1 → 33% & battery 2 → 82%

e. Consider the diagram below which shows the 1st cycle of batteries 1 & 2.



V_1 = 3 V, V_2 = 2.8 V, t_1 = 10 h, t_2 = 20 h

What can explain for the differences in performances with respect to the first charge/discharge cycle?

- o Battery 1 : Bigger difference between V_{charge} and $V_{discharge}$ → higher overpotential → higher internal resistance
- o Battery 1 : Change in operating temperature
- o Battery 2 : Loss in charge and discharge capacity because of loss of active material. Active material became inactive or has been dissolved
- o All of the above

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Final model quiz

Section 2.1

Question 1

Consider the following information about an electric car. Let us assume that the car consumes the equivalent energy of 0.5-1 litre of gasoline to drive 15 km.

- 1 Wh = 3.6 kJ → Energy to lift 100 kg 3.7 meters
- 1 cal = 4.2 J → Energy to raise the temperature of 1 g water with 1 degree
- 1 MJ = 0.28 kWh → Energy to accelerate a car of 1000 kg to 161 km/h (no air resistance)
- 36 MJ = 10 kWh → Energy content of 1 liter gasoline

What is the estimated energy required to drive this light electric car for 150 km?

- o 50-100 kWh
- o 100-200 kWh
- o 200-500 kWh
- o >500 kWh

Question 2

Imagine a gasoline-powered car and an EV, both requiring 100 kWh for a journey. Assume that the conversion from chemical to mechanical energy is 25% efficient for the gasoline car and 90% efficient for the electric car. The state-of-the-art lithium-ion batteries have an energy density close to 250 Wh/kg, which is still relatively small compared to 12,900 Wh/kg for gasoline.

What is the calculated weight of fuel required for the gasoline-powered car and what is the weight of the EV battery?

- Gasoline weight → 7.75 kg and EV battery weight → 400 kg
- Gasoline weight → 31 kg and EV battery weight → 444 kg
- Gasoline weight → 7.75 kg and EV battery weight → 444 kg
- Gasoline weight → 400 kg and EV battery weight → 31 kg

Question 3

What is the function of a Battery Management System?

- To monitor the state of the individual cells and manage how the individual cells are charged and discharged.
- To detect when the battery malfunctions
- To detect when the battery is completely charged or discharged
- All of these

Question 4

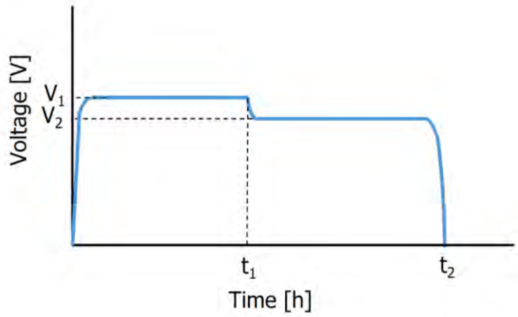
What are the challenges faced by current Li-ion battery technologies? Note: Multiple answer may be correct.

- ☐ Current lithium-ion batteries are close to the maximum theoretical energy density of 280Wh/Kg
- ☐ Safety concerns related to the liquid electrolytes in these batteries
- ☐ Lithium is found only in a few areas of the world and is expensive to extract from oceans
- ☐ Li-ion batteries have very low energy densities compared to other battery technologies like lithium sulfur and lithium air

Section 2.2

Question 1

Two batteries are galvanostatically tested (constant current, 6A) to determine their electronic performances. The first charge/discharge cycle can be seen in the figure below and appears to be the same for both batteries. The mass of a single battery = 0.2 kg.
Given V_1 = 3V, V_2 = 2.8V, t_1 = 10h, t_2 = 20h



a. Calculate the specific capacity of the batteries (in mAh/g).
b. Calculate the specific energy density of the batteries (in Wh/kg).
c. Calculate the Coulombic efficiency (%) of the batteries.
d. Calculate the energy efficiency of the batteries.
e. What is the tested C-rate? (Assume that theoretical capacity is achieved after the first charge).

- o 1
- o 10
- o 1/10
- o 0.2

d. In case of a low power demand from the vehicle in case of hybrid energy storage

- o Battery delivers the power and is simultaneously charging the ultracapacitor.
- o Both battery and ultracapacitor contribute to the total power supply.
- o Only ultracapacitor delivers the power.

Section 2.3

Question 1

LixFePO4 is the positive electrode with x=1 at a potential of 3.4V vs Li-metal, and graphite is the negative electrode on average at 0.2 V vs Li-metal.

Match the half redox reactions and the total reaction for this battery during discharge with the reaction type (**oxidation**, **reduction**, **total reaction**)

$LiC_6 \rightarrow Li^+ + e^- + C_6$. ___________________________

$FePO_4 + Li^+ + e^- \rightarrow LiFePO_4$. ___________________________

$LiC_6 + FePO_4 \rightarrow C_6 + LiFePO_4$. ___________________________

Question 2

What is the specific capacity of the $LiFePO_4$ positive electrode?
Given: Molecular mass Li: 6.9 g/mol, Fe: 55.8 g/mol, P:31 g/mol, O:16 g/mol, C:12 g/mol.

Question 3

What is the theoretical energy density of this battery?
Molecular mass Li: 6.9 g/mol, Fe: 55.8 g/mol, P:31 g/mol, O:16 g/mol C:12 g/mol and Faraday's number is 96485 C/mol.

Question 4

Why is the answer in Question 6 much higher than the practical energy density?

- Because of the internal resistance
- Because materials never achieve their theoretical capacity
- Because the weight of the other battery parts was not taking into account
- All of the above

Section 2.4

Question 1

When is a EV battery considered to be at the end of its lifetime and needs to be replaced?

- When the battery capacity becomes zero.
- When the battery capacity is below a minimum accepted capacity.
- When the battery capacity is above a minimum accepted capacity.
- None of the above

3 Power electronics for EV

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3.1 Power electronics in electric cars

In this section, we will look at the basics of power electronics. First, we will look at what is a power electronic converter. Then will look at the different converter types based on whether the power is AC and DC, the direction of power flow and the presence of isolation. Finally, we will look at the converters in an electric and understand the concept of four-quadrant converter operation.

A power electronic converter is an electronic device made of high power semiconductor switches that use different switching states to change the magnitude and waveform of the voltage and current between the input and output.

A semiconductor switch is the basic building block of any power electronic converter. We can see the schematic representation and real photo of a semiconductor switch in Figure 3.1. In this case, it is an insulated-gate bipolar transistor or called as IGBT in short. These power electronic switches are able to turn on and turn off at high switching frequencies ranging from hundreds of hertz up to hundreds of kilohertz. In other words, they are able to turn on and turn off within half a microsecond. The new silicon carbide or Gallium nitride (GaN) based switches turn on and off even faster within tens of nanoseconds.

In this particular IGBT switch, an antiparallel diode is included that allows reverse currents. The other commonly used semiconductor devices in power converters are Metal-Oxide-Semiconductor Field-Effect Transistor or MOSFETs as they are commonly called and thyristors.

The most common way to classify power converters is based on whether the input and output are AC or DC, that is if it is alternating current or is direct current. Based on this classification, we can have four types of power converters, namely a DC to DC converter, a DC to AC converter which is commonly called an inverter, an AC to DC converter which is commonly called a rectifier and an AC to AC converter. For example, a DC to AC converter converts power from an input DC source to an output AC load.

Figure 3.1 IGBT schematic and picture

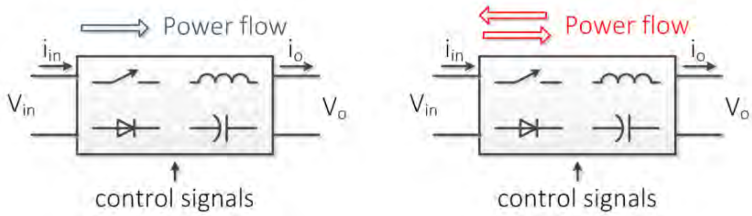


Figure 3.2 Uni- and bi-directional power flow type of converters

The second way to classify converters is based on if they facilitate unidirectional or bidirectional power flow (see Figure 3.2). Typically, unidirectional converters use diodes at the output in order to allow power flow in one direction only. In case of bidirectional power converters, semiconductor switches like MOSFETs or IGBTS are used on both input and output sides.

A third way to classify converters is based on whether there is transformer isolation between input and output, as depicted in Figure 3.3. Isolation in power converters is primarily required for safety reasons. For example, all mobile phone chargers are isolated so that the 5V low voltage output is safe to touch even though the input is from 110V or 230V AC. Further, the transformer used for galvanic isolation can have a different turn ratio between input and output that can help in stepping or stepping down the voltage.

Table 3.1 gives you an overview of the three simple ways to classify power converters based on AC or DC power, power flow direction and presence of isolation. Different types of power converters can be developed that meet a combination of these characteristics.

With this knowledge, we can look at the four main power converters in an electric car, namely: the on-board charger, the traction battery converter, the auxiliary battery converter and the motor drive.

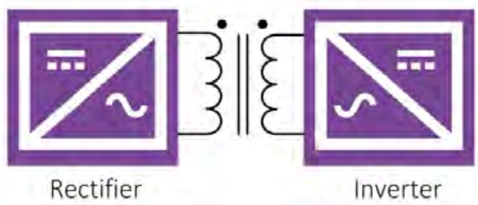


Figure 3.3 Magnetically-isolated power converters

Table 3.1 Overview of simple power converters classification

Type				
AC or DC	AC-DC	DC-AC	DC-DC	AC-AC
Magnetic Isolation	Isolated		Non-isolated	
Bidirectional power flow	Bidirectional		Unidirectional	

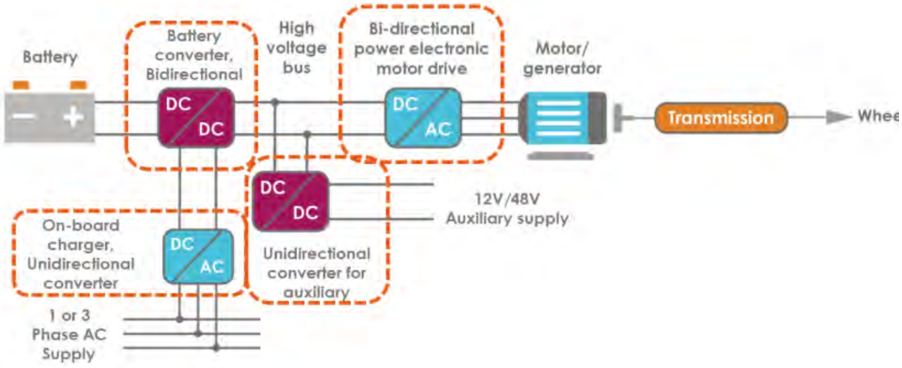


Figure 3.4 Power converters in an electric car

An electric car, as you can see in Figure 3.4, uses a central DC bus for exchanging power between the various electric components, and the converters are responsible for controlling the power flows. The on-board charger is responsible for converting the AC power from the grid to the central DC bus for the charging the traction batteries. Hence, it is an AC to DC power converter. The battery conve

rter then controls the charging or discharging of the traction batteries by either drawing or feeding power from the DC-link. Hence, the battery converter is a bidirectional DC-DC converter. Similarly, the auxiliary battery converter is used to charge the auxiliary battery by drawing power from the DC bus. Finally, the motor drive is a DC to AC inverter used to control and operate an AC motor. The motor drive is bidirectional and feeds power to the motor for propulsions and acts as an AC to DC rectifier by drawing power from the motor during regenerative braking. In some cases, the motor drive can be a DC to DC converter if the motor is a DC motor like a brushless DC motor.

In any power converter, energy is always conserved. Hence, the input and output power can be related based on the losses in the power converter, as:

$$P_{out} = P_{in} - P_{loss} \tag{3.1}$$

$$P_{in} = V_{in} \cdot I_{in} \tag{3.2}$$

$$P_{out} = V_{out} \cdot I_{out} \tag{3.3}$$

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100 \tag{3.4}$$

Where:

- P_{out} and P_{in} are the output and input power of the power converter;
- P_{loss} is the losses in the power converter;
- V_{in} and I_{in} are the input voltage and current of the power converter;
- V_{out} and I_{out} are the output voltage and current of the power converter.

Table 3.2 Overview of EV power converters classification

Converter	AC or DC	Isolation	Direction
On-board charger	AC-DC	Isolated	Unidirectional
Battery converter	DC-DC	Isolated	Bidirectional
Motor drive	DC-AC	Isolated / Non-Isolated	Bidirectional
Auxillary battery converter	DC-DC	Isolated / Non-Isolated	Unidirectional

Table 3.2 gives an overview of the power converters in an electric car and their characteristics for AC and DC power flow, power flow direction and isolation. It is important to note here that one or both of the on-board charger and the battery converter has to be isolated so that there is isolation between the battery and the AC grid for safety reasons. Secondly, both the traction battery converter and the motor drive must be bidirectional. These converters are also shown in the car schematic in Figure 3.5.

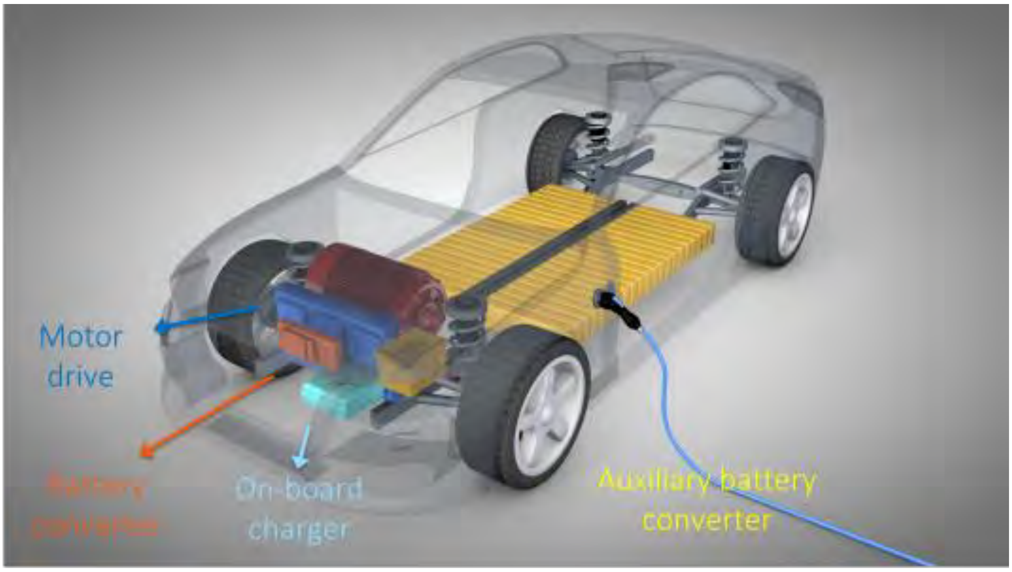
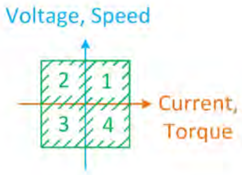


Figure 3.5 Power converters in an electric car schematic

Table 3.3 Combination of motor inverter voltage and current polarity

Voltage	Speed	Current	Torque	Quadrant
+	+	+	+	1
+	+	-	-	2
-	-	-	-	3
-	-	+	+	4



Let us look deeper into the bidirectional power flow operation of the power converters and motors in an electric car. Any car needs the ability to both drive and brake in the forward and reverse direction. This can be represented using the four-quadrant torque-speed characteristics, as shown in Figure 3.6. The four quadrants from 1 to 4 correspond to driving in the forward direction, braking in the forward direction, driving in the reverse direction and braking in the reverse direction, respectively. Let us now look deeper into this.

For example, the first quadrant operation is when the motor has both positive polarity voltage and current, and this results in forward driving of the car. In the case of third quadrant operation, the motor has both negative polarity voltage and current, and this results in reverse driving of the car. Or in simple words, the car moves backwards.

In the case of second quadrant operation, the motor has positive polarity voltage and but negative polarity current. This results in the wheels moving forward, but the torque is in the opposite direction. This results in regenerative braking and the car slows down while moving forward. Regenerative braking can also be implemented for operation in quadrant 4 by extracting power out of the motor using the motor drive and to charge the traction batteries.

If a DC motor and a DC electric drive are used, we can generalise that the torque magnitude and direction is dependent on the current magnitude and direction, respectively. Similarly, the speed of rotation and direction is dependent on the voltage magnitude and polarity, respectively. So in order to control the torque and rotation of a motor, we need a motor drive that can control the current and voltage of the motor, respectively.

In Table 3.3, we can see the four combinations of motor inverter voltage and current polarity and the corresponding motor rotation and torque for a DC motor. Each of these four unique

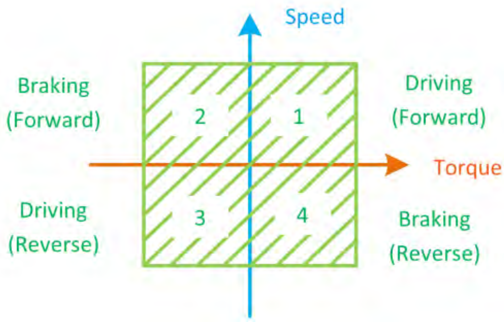


Figure 3.6 Four quadrants operation

combination results in operation in one of the four quadrants of the torque-speed characteristics.

Electric cars, however, often use AC motors and their control is more complicated than DC motors. In the case of AC motor, the forward and reverse rotation of the motor is controlled by changing the phases of the AC supply voltage from the motor drive. In order to control the torque and speed, a variable speed motor drive is used that changes both the AC voltage magnitude and frequency in order to control the rotation speed of the AC motor. Generally, the speed of the motor can be increased by applying an AC voltage of a high frequency.

Let us now analyse the equations used to describe the driving and braking of an electric vehicle. The **kinetic energy** E_{KE} (in Joules, J) of the car can be related to the mass of the vehicle m (in kilograms, kg) and its velocity v (in meter per second, m/s):

$$E_{\mathrm{KE}}=\frac{1}{2}\mathrm{m}\cdot\mathrm{v}^2 \tag{3.5}$$

The energy delivered to the car, E_{ev}, by the drivetrain and the battery over a period t when delivering an average power P_{ev}, assuming no losses, can be obtained by:

$$E_{\mathrm{ev}}=P_{\mathrm{ev}}\cdot t \tag{3.6}$$

The battery power P_{batt} can be expressed as a product of the voltage of the EV battery V_{batt} (in volts, V) and the charging/discharging current of the battery I_{batt} (in amperes, A) as:

$$P_{\mathrm{batt}}=V_{\mathrm{batt}}\cdot I_{\mathrm{batt}} \tag{3.7}$$

Based on the EV battery power, the corresponding C-rate of the battery pack can be estimated. The C-rate, as we saw in the previous chapter, is the ratio of the battery power (P_{ev} in kilowatts, kW) to the nominal energy capacity of the battery (E_{nom} in kilowatt-hour) in kWh. As the charging current increases, so does the C-rate:

$$\text{C-rate}=\frac{P_{\mathrm{ev}}}{E_{\mathrm{nom}}} \tag{3.8}$$

An alternate definition of C-rate is the ratio of the battery charging/discharging current I_{batt} to the nominal ampere-hour of the battery Q_{nom} (in Ah):

$$\text{C-rate}=\frac{I_{\mathrm{batt}}}{Q_{\mathrm{nom}}} \tag{3.9}$$

Now we look into the drivetrain of hybrid electric car. The electric drivetrain of an HEV can be envisaged to have the following components:

- Batteries as energy storage.
- DC-DC Converter for battery (bidirectional)
- DC-AC Converter for motor drive (bidirectional)
- Motor for driving
- Generator for charging battery from combustion engine

- Combustion engine (with powersplit)

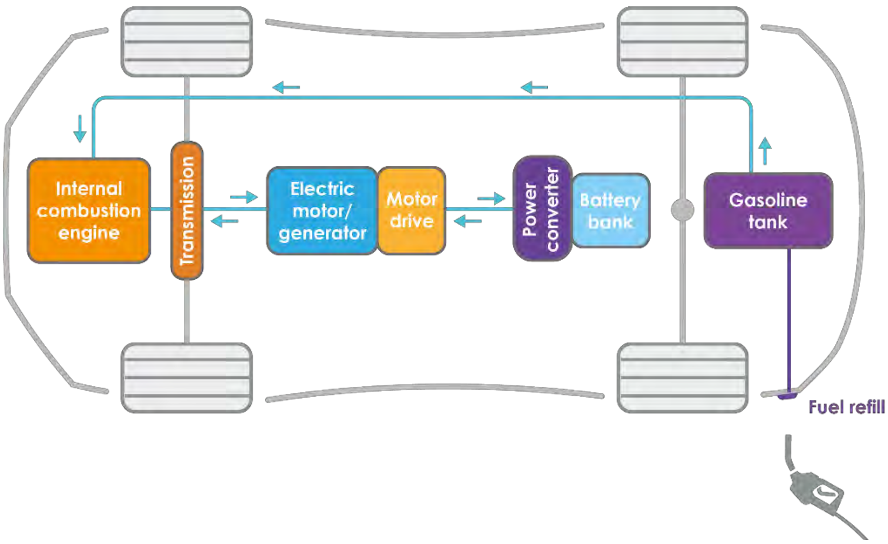


Figure 3.7(a) HEV drivetrain in parallel

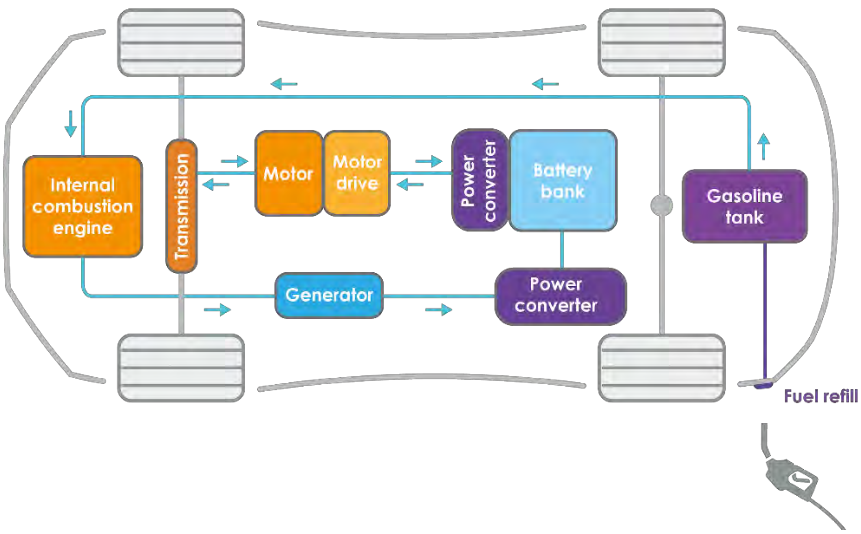


Figure 3.7(b) HEV drivetrain in series

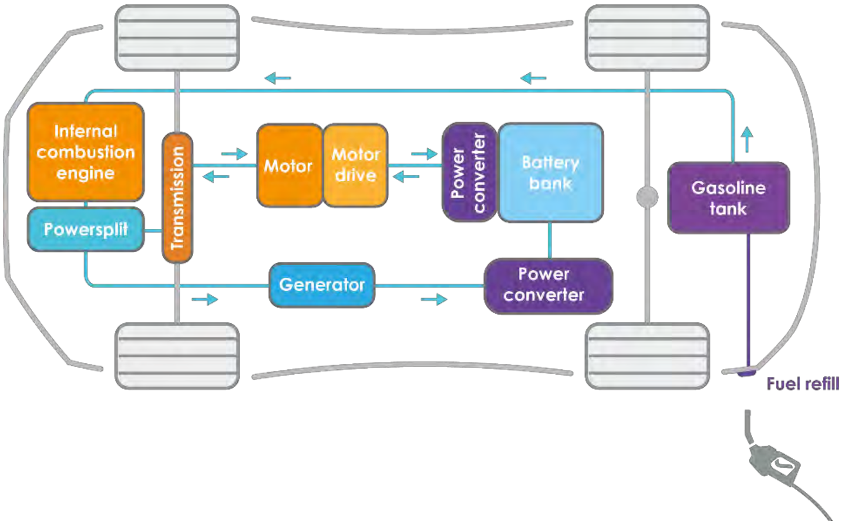


Figure 3.7(c) HEV drivetrain in series-parallel

A typical electrical drivetrain of an HEV is shown in the figure above. Motor and generator here are separated. Generator is usually driven by the combustion engine. Typical voltages can be, for example, a battery voltage of 200 V, while the voltage of the DC link is 500 V. The link between the DC/DC power converter of the battery and DC/AC converters of the motor drive is called DC voltage link and contains as an energy storage a large capacitor.

The used DC/DC battery power converter has to step-up (boost mode) the voltage in case of driving the car or accelerating while the battery is discharged. The energy flow is from the battery to the 500V DC link. On the other side by decelerating the energy is stored in the battery, the voltage of the DC link has to be stepped down (buck mode) and the energy flow is from the DC link to the battery.

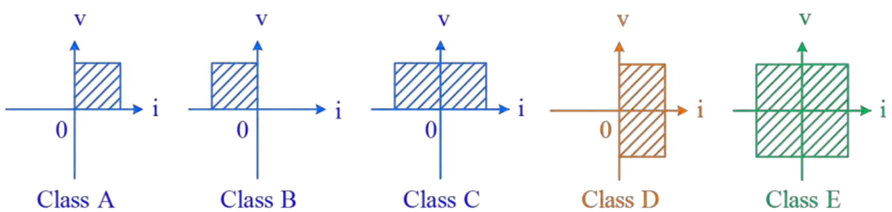


Figure 3.8 DC-DC class converter types

To wrap up, we looked at what is power electronic converter and how power semiconductor switches play a key role in their operation. We learnt about different types of power converters based on AC or DC, isolation and power flow direction. The four key power converters in an electric car are the on-board charger, traction and auxiliary battery converter and the motor drive. The motor drive facilitates in controlling the voltage, frequency, phase and current supplied to the motor resulting in four-quadrant operation. Different types of converters can be used to facilitate operation in one or more of the quadrants. These converters are referred to as Class A to Class E converters based on which quadrants they can operate in. In electric cars, Class E converters are used in the motor drive to allow operation in all four quadrants. Figure 3.8 features an overview of the above-mentioned converter classes. We also compare different HEV drivetrain topology.

Practice problems

Question 1

Why is the motor drive a bidirectional converter?

- It needs to feed power to the motor for motoring and draw power from the motor for regenerative braking.
- DC/AC converters are always bidirectional.
- Unidirectional converters have a lower efficiency

Question 2

In an EV drivetrain shown in Figure 3.4, the battery voltage is 200 V and the high voltage DC bus is 500 V.

What happens when power from the battery is used for powering the wheels in the reverse direction while the EV moves backwards?

- The battery is charged and the DC-DC battery converter operates in buck mode.
- The battery is discharged and the DC-DC battery converter operates in buck mode.
- The battery is discharged and the DC-DC battery converter operates in boost mode.
- The battery is charged and the DC-DC battery converter operates in boost mode.

Question 3

The input voltage and current of a DC-DC power converter are 200V and 20A, respectively. The output voltage is 800V. Then what is the output power and output current assuming there are no losses?

- Output power=400 W, Output current=50A
- Output power=40 kW, Output current=5A
- Output power=4 kW, Output current=50A
- Output power=4 kW, Output current=5A

3.2 DC-DC converters: Part 1

In this lecture, we focus on DC to DC type of power electronic converters that facilitate the conversion from one DC voltage level to another DC level. In particular, we will focus on the buck or step down converter.

The main learning objectives will fall under three questions. First, how do DC to DC converters work? Second, what are the operating states of a buck converter? Third, what is the ratio between the input voltage and output voltage of a DC to DC buck converter?

The DC to DC converter is responsible for stepping up or down the input voltage V_{in} to the desired level of voltage at the output V_o, as shown in the generic scheme of Figure 3.8. The input DC source can be for instance a DC link called high voltage DC bus. The output can be connected to a battery, for example. Based on the input to output voltage ratio, we recognize the buck (or step down) converter where the output voltage is lower than the input voltage. The other converter is stepping up the voltage and is called the boost converter.

Figure 3.9 shows the typical layout of power electronics components in a BEV. As you could see in Figure 3.4 in the previous section, the battery is connected to the high voltage (HV) bus via a bidirectional DC/DC converter.

When the power transferred from the High voltage bus to the battery, which charges the battery through the regenerative-braking. The voltage on the high voltage bus is stepped down to a lower voltage level for the battery, therefore this battery converter is working in the buck mode. In Figure 3.10 you can see the simplified diagram of the buck converter. At its left side is the higher voltage the $V_{HV\text{-}bus}$, and the lower battery voltage V_{batt} is at its right side. In this case, the higher voltage at the left side is the input voltage V_{in} and the lower voltage at the right side is the output voltage V_o.

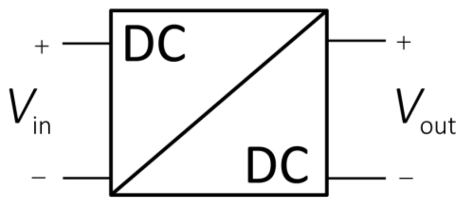


Figure 3.8 Generic scheme of a DC-DC converter

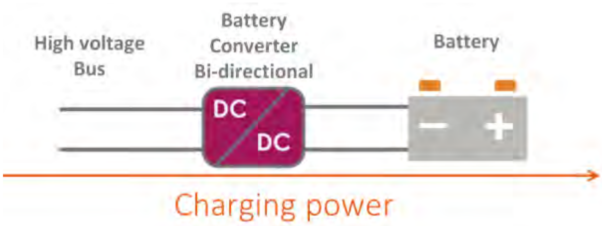


Figure 3.9 Battery charging power flow direction

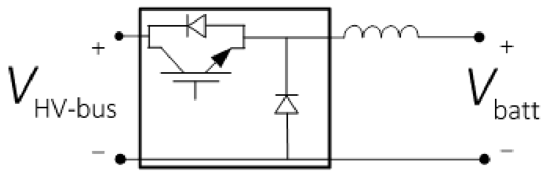


Figure 3.10 Buck converter in the BEV

In Figure 3.11, we show the circuit diagram of a simplified buck converter which includes only a switch, a diode, and an inductor. The inductor is the main responsible for smoothing out the output current. In that figure, we can see the output voltage of the converter versus time. We define T_{on} as the on-time of the switch whereas T is the total time of a period. If the switch is on, then the output voltage is equal to the input voltage. And, if the switch is off, then the output voltage is equal to zero. The output voltage is changing between two values, V_{in} and zero and thus has a large ripple. As we can see, the average output voltage $V_{o,av}$ in the dotted blue line depends on the ratio of on-time of the switch and the total period. The diode is called freewheeling diode which takes over the load current in the interval when the switch is off.

Based on the simple diagram, if we add a capacitor in parallel, then the capacitor will help reduce the voltage ripple, from the black waveform to the one shown in blue. As we increase the value of the capacitor, the amount of the voltage ripple is further reduced

We mentioned that the capacitor helps reduce the output voltage ripple. Indeed the capacitor suppresses the rate of change of the output voltage which is reflected as the current of the capacitor. This is mainly because the capacitor can maintain the voltage to some extent by absorbing or releasing it is stored energy E_c which depends on the capacitance and the square of the DC voltage across the capacitor.

$$i_c = C \cdot \frac{dv_c}{dt} \tag{3.8}$$

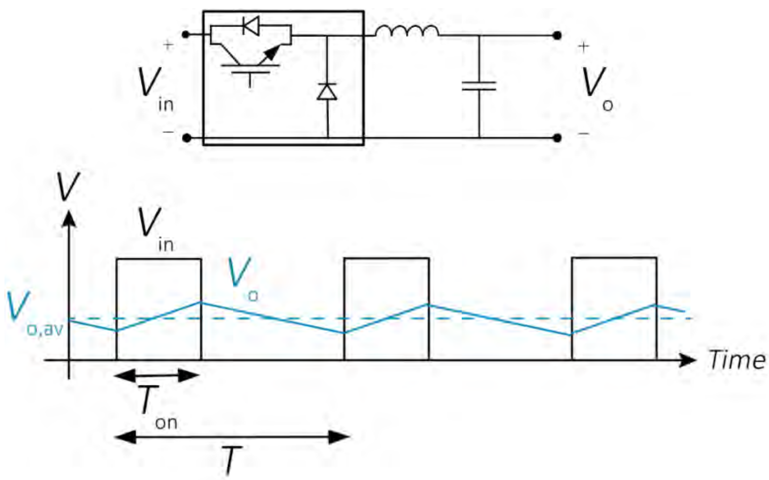


Figure 3.11 Buck converter: voltage output when a capacitor is used

$$E_c = \frac{1}{2} C \cdot v_c^2 \tag{3.9}$$

While the capacitor is used in parallel to the load maintain the level of DC voltage, an inductor can be employed in series to maintain the level of DC current. The inductor is smoothing out the rate of change of current, that is reflected as the voltage across the inductor. Similarly, the inductor is able to release or absorb its stored energy, which depends on the inductance and the square of the current passing through the inductor.

$$v_L = L \cdot \frac{di_L}{dt} \tag{3.10}$$

$$E_L = \frac{1}{2} L \cdot i_L^2 \tag{3.11}$$

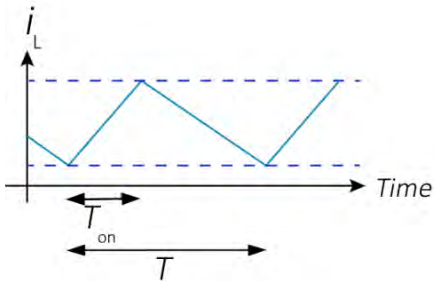


Figure 3.13 Inductor current in the buck converter

Let us now apply the buck converter on charging the battery through the regenerative-braking. A battery is connected to the output and the voltage is the battery output voltage V_o. We can consider two states of operation for the buck converter, as shown in Figure 3.12. In the first operating state, the input source is connected to the output where it stores some energy in the inductor and charges the battery. Note that the voltage of the inductor V_L is positive since the input voltage is larger than the output battery voltage. During the second state, the switch turns off, and accordingly the input is disconnected from the inductor. During this state, the energy stored in the inductor is fed to the output

Let's now see how the current of the inductor changes during these two operating states, as the inductor current is shown in Figure 3.13. During the first state, the current of the inductor increases where the current derivative depends on the difference of the input and output battery voltage:

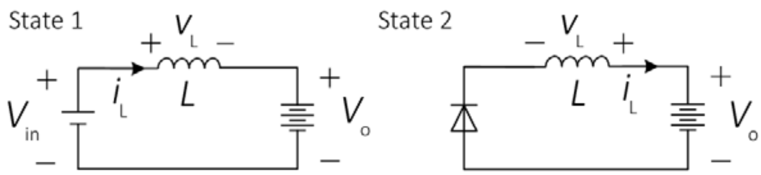


Figure 3.12 Two states of a buck converter operation

$$\frac{di_L}{dt} = \frac{V_{in}\text{-}V_o}{L} \tag{3.12}$$

During the second operating state, the voltage across the inductor is equal to minus of the output voltage. During this state, the inductor releases the stored energy to the battery (which has some internal resistance). The current derivative only depends on the output voltage:

$$\frac{di_L}{dt} = \frac{-V_o}{L} \tag{3.13}$$

Let's see the voltage over the inductor during both on and off states of the switch. During one switching cycle in steady state, it is important to note that the average inductor voltage must be equal to zero. This means that the green area in Figure 3.14 during on-period is equal to the red area during the off time and as a result, the voltage of the inductor at the beginning and the end of each cycle will remain the same. The graph shows also the time intervals T_{on} and T_{off} during which a switch turns on and turns off over a complete switching cycle, respectively. The duty cycle is defined as the ratio of on-time period divided by the complete switching cycle. The value of the duty cycle ranges from zero to one.

$$D = \frac{T_{on}}{T_{on}+T_{off}} = \frac{T_{on}}{T} \tag{3.14}$$

As we introduced before, the step-down or the so-called buck converters are widely used to reduce the level of the input voltage. The output voltage of a buck converter is the product of the input voltage and the duty cycle. In the application of the battery, converter works in buck mode, the output voltage to the battery V_{batt} is the product of the input voltage $V_{HV\text{-}bus}$ and the duty cycle.

$$V_{batt} = D \cdot V_{HV\text{-}bus} \tag{3.15}$$

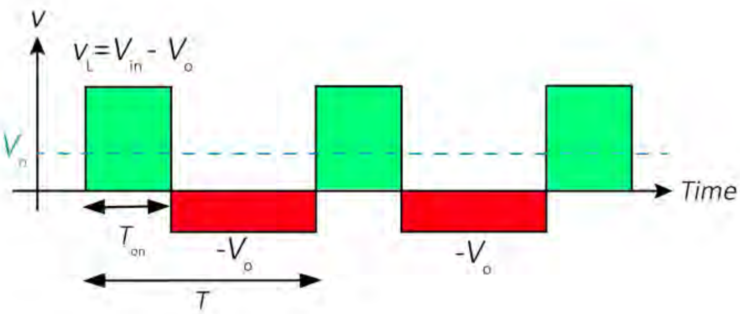


Figure 3.14 Buck converter: on- and off-time voltage change across the inductor

Finally, there are different ways to chop or step down the DC voltage, given in Figure 3.15. First, is the pulse width modulation method or the PWM method where the total time period of the signal T is fixed, and then the on-time T_{on} of the switch is changed. This method is effective when the fundamental switching frequency has to be constant. In the frequency modulation method, unlike the PWM, the on-time of the switch T_{on} remains constant and the total period *T* changes. This method is used when the variable switching frequency is needed.

To wrap up, in this section we focused on one of the most common DC to DC power converters, namely the buck or step-down converter. We evaluated two operating states of the converter during on time and off time of the switch. We introduced the concept duty cycle and saw how the output of the buck converter is simply the product of input voltage and the duty cycle.

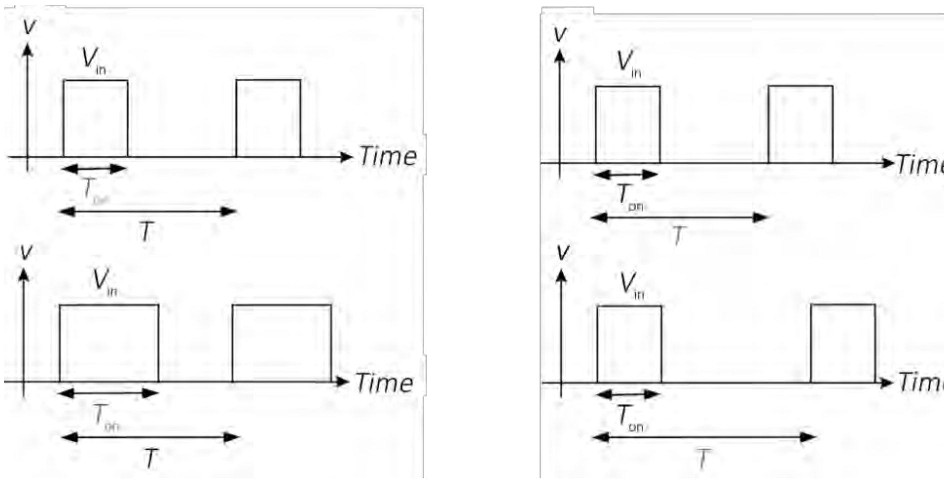


Figure 3.15 Pulse Width Modulation (on the left) and Variable Frequency Control (on the right)

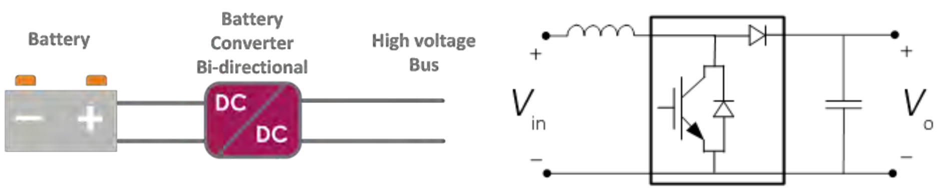


Figure 3.16 Boost converter in a BEV (on the left) and schematic (on the right)

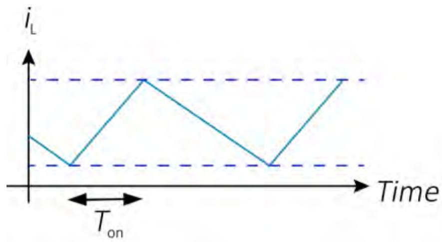


Figure 3.18 Boost converter: on- and off-time current change across the inductor

3.3 DC-DC converters: Part 2

In this DC/DC converter part 2 lecture, we go deeper into the topic of DC-DC converters where we focus on the boost and buck-boost converters.

The step-up or the boost converters are widely employed to increase the level of input DC voltage. For example, when you drive the electric car, the battery provides the power to the motor for propelling the car. Figure 3.16 shows this. In this case, the bi-directional battery converter is working in boost mode. Which is to convert the power with lower battery voltage into the power with higher voltage on the high voltage bus. Under this mode, the battery at the left side is the input voltage V_{in} and the HV-bus voltage at the right side is the output voltage V_O.

The DC to DC conversion is conducted typically through a switch and a diode. Note that due to the placement of the diode at the output, the flow of current from output to input is not possible for a boost converter. The output voltage of a boost converter is calculated taking into account the input voltage and the duty cycle of the switch.

$$V_O = \frac{V_{in}}{1-D} \tag{3.16}$$

This can be proved by a simple equation. Transferring power to higher output voltage levels is possible in the boost converter as the energy stored in the inductor by the input voltage source increases during the on-time period.

Let us consider the behaviour in Figure 3.17. During the on-state of the switch, the voltage across the inductor is equal to the input voltage that is shown by the green area, and the

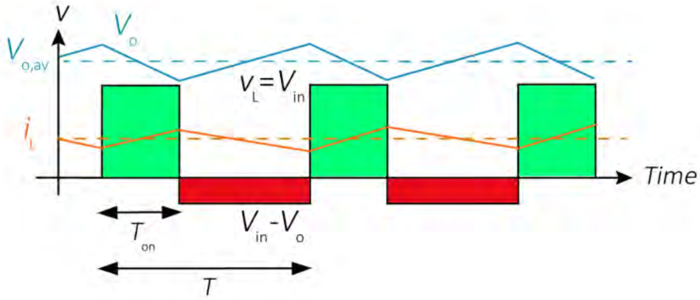


Figure 3.17 Boost converter: on- and off-time voltage change across the inductor

Table 3.4 Buck & boost operation modes, with $V_{in}>V_o$

No power flow	$V_{in}\cdot D_{S1}=V_{12,avg}=V_o$	$D_{S1}=V_o/V_{in}$
Boost operation	$V_{in}\cdot D_{S1}=V_{12,avg}<V_o$	$D_{S1}<V_o/V_{in}$
Buck operation	$V_{in}\cdot D_{S1}=V_{12,avg}>V_o$	$D_{S1}>V_o/V_{in}$

inductor current linearly increases. The capacitor supplies the load, and therefore the output voltage starts to decrease. Then, the energy stored in the inductor is provided to the output during the off-time of the switch when the voltage across the inductor is negative, as shown by the red area. During this period, the capacitor is charged where the output voltage increases. During the on-time period, the inductor current (depicted in Figure 3.18) derivative depends on the input voltage.

$$\frac{di_L}{dt}=\frac{V_{in}}{L} \tag{3.17}$$

While during the off time period, the derivative depends on the difference of the input and the output voltage.

$$\frac{di_L}{dt}=\frac{V_{in}-V_o}{L} \tag{3.18}$$

How can we make a DC to DC converter topology which would be able to step up and step down the voltage? We can combine the previous two topologies namely the buck converter and the boost converter. When we flip the boost converter and combine these two converters, we create the **buck & boost** topology.

In practice, the inductor is never ideal that there is always some ohmic losses. So a resistor is in series with the inductor. Then the topology of the buck & boost converter is redrawn into the topology shown in Figure 3.19. The output voltage is in this case battery voltage and we assume constant input voltage too. This consists of two switches which are equipped with two anti-parallel diodes. This combination is not so straightforward as this converter is a buck from left to right and a boost from right to left. Let us have a look at more details.

Let us analyse in detail the operation of the *buck & boost* converter. This converter should be able to transfer power from the higher voltage V_{in} to the lower voltage V_O and also vice versa. As it can be seen, the two switches S1 to S2 are connected across a DC voltage source V_{in}. Here, each switch consists of an IGBT with an antiparallel diode. The switches open and close alternately in such a way that when S1 is closed, S2 is open and vice versa. Note that in

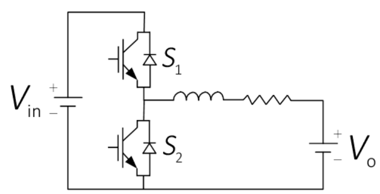


Figure 3.19 Schematic of the buck & boost converter

this topology both switches 1 and 2 cannot be closed at the same time, since the input will be short-circuited. The time of one cycle is T, and S1 is closed for a period T_{on}. It follows that the duty cycle of S1 is and S2 are, respectively:

$$D_{S1}=\frac{T_{on}}{T} \tag{3.19}$$

$$D_{S2}=1-D_{S1} \tag{3.20}$$

Let us now analyse the boost operation. If S2 is conducting, the energy is stored in the inductor. When S2 is off, the diode of S1 takes the current over and delivers energy to the higher voltage level V_{in}. The buck operation is when the switch S1 is conducting. When S1 is off the freewheeling diode of S2 takes the current over. By varying duty cycle D from zero to 1, we can vary the current direction and whether it is buck or boost operation. The average current can flow in either direction depending on the magnitude of the average voltage across terminal 1 and 2 V_{12} and the output voltage V_O. Whether the converter is working on buck mode or boost mode can be determined by comparing the duty cycle to the ratio between the input voltage V_{in} and the output battery voltage V_O, as it is summarized in Table 3.4. The polarity of the DC voltage V_O remains fixed and current is changing the direction. It is hence a two-quadrant converter.

Now we map the buck-boost converter back to the bi-directional battery converter of the EV. When the regeneration power flows from the motor to the battery through the HV-bus, the converter works as buck mode. It happens when D_{S1} creates average voltage on terminals 1 and 2 larger than battery voltage. On the other side, this converter works in boost mode when the battery powering the motor. It happens when D_{S1} creates average voltage on terminals 1 and 2 smaller than battery voltage.

In other words, when recovering the kinetic energy from the vehicle, the device operates in buck mode, where the voltage level is decreased to a level that is within the safe voltage range of the battery as shown in Figure 3.20. When propelling the vehicle, the device operates in boost mode and the DC voltage is regulated to output a higher voltage level for the electric motor drive and motor. As already concluded, the DC-DC battery converter should work in two quadrants as a class C converter and the current must be able to reverse.

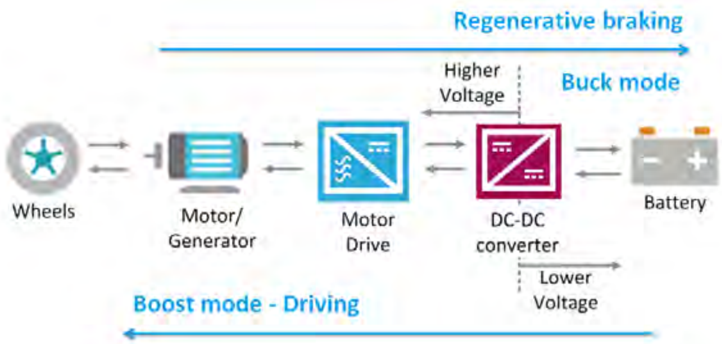


Figure 3.20 Buck and boost mode of operation for the battery converter

In reality, the battery converter is much more complex, as shown in Figure 3.21. If isolation is needed between input and output, a dual active bridge converter with a high-frequency transformer can be used.

To wrap up, boost or step-up converters have one switch and can help in boosting the voltage from a lower input to a higher output voltage. To obtain bidirectional power flow, a buck and boost converter can be created by combining buck and boost converter. The buck and boost converter can operate in two quadrants by changing the direction of the current. Several other DC to DC power converter topologies are possible that can facilitate four-quadrant operation and provide isolation as the requirements may be.

The last point worth discussing in **electromagnetic compatibility** or EMC. Electromagnetic compatibility defines an electrical system's ability to remain neutral in the vicinity of other systems. In automotive systems, all electrical equipment must be able to function in close proximity to each other without producing emissions that directly or indirectly degrade the performance of other equipment. Modern vehicles have numerous electronic systems, including electronic ignition, electronic fuel injection, ABS, airbags, radio, car phone and navigation systems. The introduction of high voltage electric machines and high-frequency switching controllers will raise further EMC problems for vehicle manufacturers.

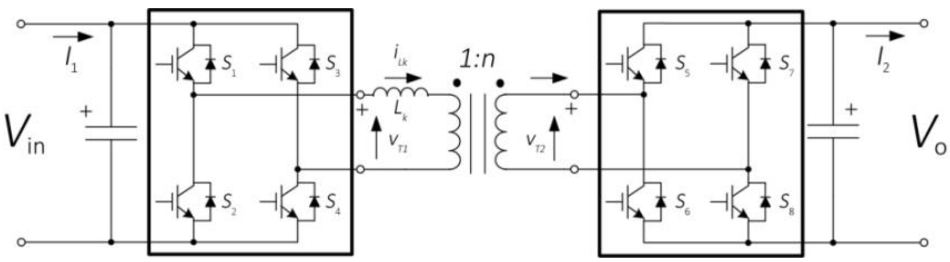


Figure 3.21 Real battery converter with isolation

Practice problems

Question 1

In the context of the buck converter diagram given in Figure 3.11, consider the following two statements.

A. The inductor in series is responsible for smoothing out the output current.

B. The capacitor in parallel reduces the output voltage ripple.

Which option is correct?

- Both statements are true
- Only statement A is true
- Only statement B is true
- Both statements are false

Question 2

Consider the following two statements.

A. In the pulse width modulation method or the PWM method, the total time period of the signal T is changed, and the on-time T_{on} of the switch is fixed.

B. In the frequency modulation method, unlike the PWM, the on-time T_{on} of the switch changes, and the total period T remains constant.

Which option is correct?

- Both statements are true
- Only statement A is true
- Only statement B is true
- Both statements are false

Summary

We have come to the end of this module on EV charging technology. In the first lecture, we saw various charging methods for EVs. The three common ways are conductive charging, inductive charging and battery swap. Conductive charging is the most common charging method right now and it has two categories: AC and DC charging. The second method is inductive charging and consists of two types: static and dynamic charging. The final method is battery swap. These charging methods have their own advantages and disadvantages. While battery swap provides the quickest "charging" time, it faces a big challenge in requiring standardisation across EV manufacturers for the battery and car design. Inductive charging provides maximum convenience to the user but has a higher cost and relatively lower efficiency than conductive charging.

The second lecture was on AC charging of electric vehicles. In its simplest form, AC charging uses an onboard charger to convert AC power from the conventional AC grid to direct current or DC power to charge the traction battery. Then we saw the essential components needed in an AC charging station for a safe and reliable charging process. There are four main types of AC charging connectors: Type 1, Type 2, Type 3 and proprietary connector used by Tesla. The proximity and control pilot of Type 1 and Type 2 chargers provide the control of the charging process. Finally, we understood how a simple formula could be used to estimate the charging power and charging time for AC charging.

The third lecture was on DC charging of electric vehicles. We looked at the power flow for DC charging from the DC charger to the EV battery. There are five types of DC charging connectors used globally: CCS-combo 1, CCS-combo 2, Chademo, Tesla DC connectors and the Chinese GB/T connector. Even though DC charging is quite attractive in the sense of high power charging with short charging times, fast charging limited due to the maximum power that the charging cable and EV battery can handle and its impact on the battery lifetime.

The fourth part was on smart charging of electric vehicles, vehicle-to-grid technology and the necessary ICT protocols. Smart charging is a series of intelligent functionalities to control the EV charging power in order to create a flexible, sustainable, low cost and efficient charging environment. There are several benefits of smart charging and it has huge potential: EV charging can be controlled based on renewable generation, energy prices, grid loading and how the EV can be used as a storage and as an emergency power supply. Vehicle-to-grid is a special case of smart charging where the energy from the EV battery can be used to feed power to homes, buildings and to the grid.

The next lecture looked at charging electric cars as an evolving ecosystem with many different machines and stakeholders that must be able to exchange information using various protocols. Open protocols will be crucial for the development of the charging infrastructure market. Finally, we learnt about current and future trends in EV charging technology through the case study of ABB charging infrastructure.

Final Quiz

Question 1

Why are SiC semiconductor devices preferred over traditional Si semiconductor devices?

- SiC semiconductor devices are cheaper than their Si counterparts.
- SiC has a lower bandgap than Si devices and hence lower conduction losses.
- Converters with higher switching frequency and smaller passive components can be built.

Question 2

Why is the motor drive a bidirectional converter?

- It needs to feed power to the motor for motoring and draw power from the motor for regenerative braking.
- DC/AC converters are always bidirectional.
- Unidirectional converters have a lower efficiency

Question 3

An electric car is moving in the reverse direction and the speed is continually reducing. If the x-axis indicates the Torque and the y-axis the Speed, then in which quadrant is the operation of the electric car in the torque-speed graph?

- Fourth quadrant
- Second quadrant
- Third quadrant

Question 4

In an EV drivetrain shown in Figure 3.4, the battery voltage is 200 V and the high voltage DC bus is 500 V.

What happens when power from the battery is used for powering the wheels in the reverse direction while the EV moves backwards?

- The battery is charged and the DC-DC battery converter operates in buck mode.
- The battery is discharged and the DC-DC battery converter operates in buck mode.
- The battery is discharged and the DC-DC battery converter operates in boost mode.
- The battery is charged and the DC-DC battery converter operates in boost mode.

Question 5

The input voltage and current of a DC-DC power converter are 200V and 20A, respectively. The output voltage is 800V. Then what is the output power and output current assuming there are no losses?

- Output power=400 W, Output current=50A
- Output power=40 kW, Output current=5A
- Output power=4 kW, Output current=50A
- Output power=4 kW, Output current=5A

Question 6

The input voltage and current of a DC-DC power converter are 200V and 20A, respectively. The output voltage is 800V. What is the output current and output power if the converter has an efficiency of 90%?

- Output power=36 kW, Output current=45A
- Output power=3.6 kW, Output current=4.5A
- Output power=400 W, Output current=50A
- Output power=4 kW, Output current=50A

Question 7

What is the C-rate of an EV battery back with a nominal capacity of 100Ah and voltage of 400V and charging with a power of 80,000 W (eighty thousand watts)?

- 1C
- 0.5C

- o 2C
- o 2.5C

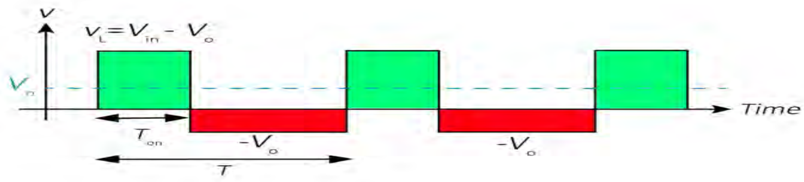
Question 8

A DC/DC buck converter converts 42V to 14V. The input current is 10A.

a. If the efficiency of the converter is 100% what will the output current be?
b. If the switching is 50 kHz, what will the period be?
c. What is the on-time of the transistor?

Question 9

Match the operating states of a buck converter to the correct buck converter diagrams, writing if they belong to **state 1** or **state 2**.



- The input source is connected to the output where it stores some energy in the inductor.__________
- The voltage across the inductor is equal to minus of the output voltage. __________
- The switch is turned off, and accordingly the input is disconnected from the inductor. During this state, the energy stored in the inductor is fed to the output. __________
- The current of the inductor increases where the current derivative depends on the difference between the input and output voltage. __________
- The inductor releases the stored energy to the resistive load, and the current derivative only depends on the output voltage. __________

Question 10

Consider the following two statements.

A. When regenerative braking power is supplied from the motor to the battery via the high voltage bus, a DC-DC converter in buck mode is used to step down the voltage.
B. When power is supplied from the battery to the motor via the high voltage bus, DC-DC converter in boost mode is used to step up the voltage.

Which option is correct?

- o Both statements are true
- o Only statement A is true
- o Only statement B is true
- o Both statements are false

Question 11

A DC/DC boost converter converts 14 V to 42 V. The input current is 10A.

a. If the efficiency of the converter is 100% what will the output current be?
b. If the switching is 100 kHz, what will the period be?
c. What is the on-time of the transistor?

Question 12

Match the operating states of a boost converter to the switch state, writing whether the phenomena described happened during the **on** or **off** switch state.

- The voltage across the inductor is equal to the input voltage. ___________
- The capacitor is charged. ___________
- The voltage across the inductor is given by the difference of the input and output voltage. ___________
- The capacitor supplies the load, and therefore the output voltage starts to decrease. ___________
- The energy stored in the inductor is provided to the output . ___________

Question 13

Consider the following two statements in relation to a buck and boost converters (as shown in Figure 3.19).

A. The system operates as buck converter when $D_{S1} > {}^{V_o}/_{V_{in}}$.

B. The system operates as boost converter when $D_{S1} < {}^{V_o}/_{V_{in}}$.

Which option is correct?

- o Both statements are true
- o Only statement A is true

- Only statement B is true
- Both statements are false

Summary quiz:

Question 1

What type of DC/DC power converter is required in order to realize bidirectional power flow from an EV battery?

- o Two quadrant converter with changing current polarity
- o Two quadrant converter with changing voltage polarity
- o One quadrant converter
- o Two quadrant converter with changing voltage and current polarity

Question 2

How is the duty ratio in DC/DC converters defined?

- o Ratio of frequency $f_s = {}^{1}/_{T}$ to the frequency of the external signals.
- o Ratio D = ${}^{T_{off}}/_{T}$.
- o Ratio D = ${}^{T_{on}}/_{T}$.
- o Ratio D = ${}^{T_{on}}/_{T_{off}}$.

Question 3

While accelerating the car with 200 V battery and 500 V DC link, the battery voltage:

- o Has to stepped-down with the DC/DC converter (buck mode).
- o Has to stepped-up with the DC/DC converter (boost mode).
- o Has to stepped-up/down with the DC/DC converter (buck-boost mode).

Question 4

Consider the following data: Voltage of the DC bus $V_{HV\text{-}bus}$=500 V , battery voltage V_{batt}=200 V , R=50 mΩ, L=500 µH, switching frequency f=50 kHz.

a. While decelerating the car with 200 V battery and 500 V DC link, the DC link voltage:
- o Has to stepped-down with the DC/DC converter (buck mode).
- o Has to stepped-up with the DC/DC converter (boost mode).
- o Has neither to be stepped-up/down.

b. When the duty cycle D_{S1} of 0.45 is used for S1, the current I_{av} is:
- o 200 A and is charging the battery.
- o 500 A and is charging the battery.
- o 500 A and is discharging the battery.
- o Neither charging nor discharging the battery.

c. When the duty cycle D_{S1} of 0.45 is used for S1, the peak-to-peak ripple superposed on the DC current is:

- o 4.95 A
- o 4.55 A
- o 3.55 A
- o 5.55 A

d. Let us assume that the maximum C-rate of the 200V battery is 2C for both charging and discharging and it is a 1000 Ah battery pack. What is the duty cycle range for S1 that the buck-boost converter can be operated in, to be within the C-rate limits.
   - o *D*=0 to 0.2
   - o *D*=0.2 to 0.6
   - o *D*=0.2 to 0.4
   - o *D*=0.4 to 1

4 Charging technology for EV

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4.1 Introduction to charging methods for EVs

In this section we will talk about the charging methods of EVs. We all know that there is a battery pack inside the EV and it needs to be charged from time to time. There are various ways to charge it. The three most common ways are listed below.

As introduced, **conductive charging** is the most common charging method right now and it has two categories: AC and DC charge. The users have their flexibility of choosing where to charge: at home, at workplace or at a public charging station. The **inductive charging** has already existed but still not standardised yet. The third method is **battery swap**. The three methods are graphically depicted in Figure 4.1.

One of the **conductive charging** methods is AC charging, which you may already familiar with. The advantages of this charger are that the battery can be recharged anywhere there is a standard electrical outlet. It can easily communicate with the Battery Management System (BMS) thanks to the internal wiring network. This effect leads to higher performance and lower cost. On the other hand, this solution is suitable for the PHEV application in which the specific energy is lower. However, the AC power has to be converted into DC power in the car, and there is a limitation of the power output. That is because of the size and weight restrictions on the on-board charger. And, normally, AC charge needs a relatively long time.

Another category of conductive charging method is DC charging. This solution is suitable for high power designs, and the power output of fast charges is limited only by the ability of the batteries to accept the charge. The charging time of fast charger is less than one hour. The benefits of DC charge are: it can be designed with either a high or low charging rate, and is not limited in its weight and size; off-board chargers are located outside the vehicle, and this set up provides more flexibility in terms of the power that can be delivered; also, DC charge with high power requests less charging time.

Nevertheless, DC charging request higher investment for installation compare to AC charging; And you could access the DC charge port only at public charging stations. In order have a safe and reliable DC charging service, there are some challenges need to overcome. First is the adverse impact on power system: harmonic contamination and high current demand

Figure 4.1 Conductive charge (on the left), inductive charge (in the centre) and battery swap (on the right)

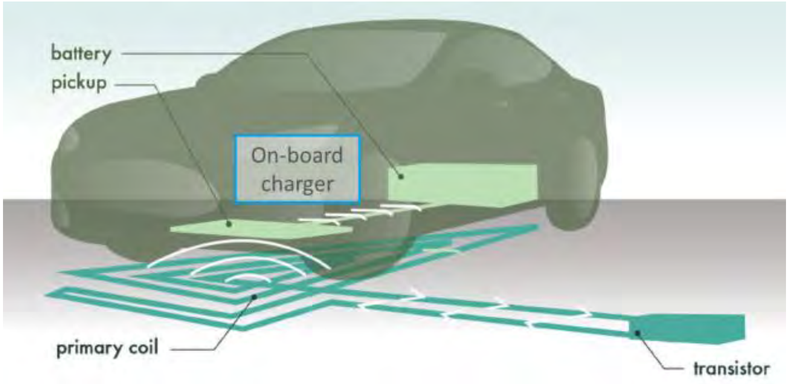


Figure 4.2 Static inductive charging

superimposing on peak hours. Second is the availability of this method is restricted due to limitations with the supply network. Finally, since the off-board chargers and the BMS are physically separated, reliable communication is important to ensure correct charging conditions. Depending on the battery type, voltage, temperature and SOC supplied by BMS, the off-board charger should adopt a proper charging method.

Inductive charge is the energy transfer from the power supply to the EV via magnetic induction coupling, based on the principle of electromagnetic induction at high frequency. A possible solution for an inductive charger is shown in Figure 4.2. The main idea behind inductive charging is the use of two electromagnetically linked coils. The primary coil is placed on the road surface, in a pad-like construction linked to the electricity network. The secondary coil is placed on the vehicle, ideally on the bottom of the car, at safe distance from the passengers. The AC is rectified and converted to a high frequency AC power within the charger station, then this high frequency power is transferred to the EV side by induction.

As we can see the wireless charging is quite convenient, and it is less mess than the conductive charging, for it has no cable. For self-driving cars, wireless communication can take care of everything, no plug behaviour needed. Moreover, inductive charge is safety-tripping, that it is suitable for all weather conditions. Of course there are also many disadvantages like high investment, limited space and weight of charge pads, limited misalignment tolerance, inevitable induction loss and the risk exposure of individuals at radiation.

There is another way to charge a car wirelessly: **dynamic charging**, shown in Figure 4.3. Similar to static inductive charging, the energy transfer from the charger to the car happens through magnetic induction coupling. In practical terms, coils connected to electric cables which used to provide the power are buried in the road. The coils emit an electromagnetic field that is picked up by vehicles driving over them and converted into electricity to charge the cars.

There are quite a lot advantages of dynamic inductive charging, for example low stand-in charging time for customers; lower DOD, which leads to a longer battery lifetime, since the car can be charged regularly; battery size can be smaller, also because the battery can be charged regularly on the road.

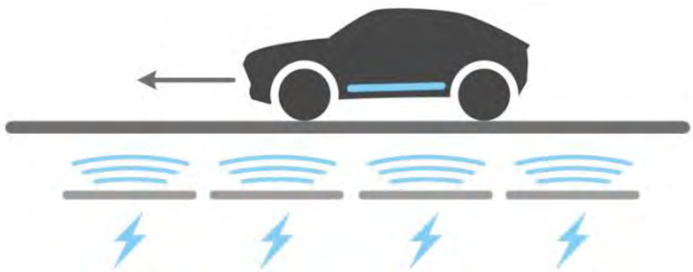


Figure 4.3 Dynamic inductive charging

The main barriers of the dynamic inductive charging are related to power transfer efficiency. The foreign objects on the road, the abrasion of the road surface and the coil structure changes inside the road building materials may impact the features of the coils and reduce the power transfer efficiency.

So far the dynamic inductive charging is still in the experimental stage because there are many challenges to standardize it. The challenges are: leakage fields in and around the car for which standardized limitations are needed; different ground clearances, car size, power level that could lead to suboptimal operations; the choice of a universal high-performance coil type for dynamic charging; real-time coil misalignment is hard to estimate for all different types of cars, but this is important for optimal control. Hence, we are still on the way to the commercially available dynamic inductive charging.

The third method we are going to introduce is **battery swap**. It works as depicted in Figure 4.4: basically switching out the depleted battery and replacing the same with a full battery. The process involves driving into a battery switching bay and an automated process will position the vehicle, switch out the current battery and replace it with a fully charged battery. The depleted batteries are charged in the station for later deployment. The benefits of battery swap is obvious, since there is no range anxiety, and you can quickly and easily refill your tank. This approach has seemingly quite some advantages over other charging technology, but to get market acceptance is a challenge. The main reasons are as follows: the requirement of a Standardized Battery Interface across multiple car manufacturers; consumer acceptance of not owning a battery and having to change the vehicle battery; to monetize the battery usage, there should be a foolproof way to estimate the batteries state of health to check for its usage pattern.

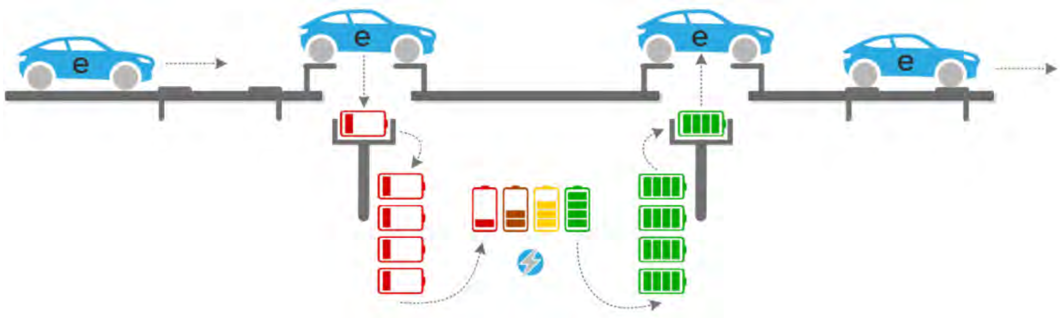


Figure 4.4 Battery swap working principle

The fourth challenge is from the safety perspective. The electrical connection between the battery and the vehicle carries a very high current, and it is this connection that would need to be made and broken each time the battery is exchanged. At best, it will cause wear and degradation at the key link between the two components. At worst, it has the potential to cause a massive discharge, with all the consequences that might ensue.

As a conclusion, there is still a long way to go to charge the battery more convenient, more efficient, stable, and economical.

Practice problems

Question 1

From the lecture, we now know that there are three ways to charge an EV. But, what is the most common charging method right now?

- o Conductive charging correct
- o Inductive charging
- o Battery swap

Question 2

Here below you see a paragraph explaining the working of charging method. Choose between the following words to correctly fill in the blanks of the below paragraph: **AC**, **inductive**, **primary**, **secondary**, **road surface**, **high**, **electromagnetic induction**, **charger station**, **two**.

_________(1) charging is the energy transfer from the power supply to the EV via magnetic induction coupling, based on the principle of _________ (2) at _________ (3) frequency. The main idea behind inductive charging is the use of _________ (4) electromagnetically linked coils. The _________ (5) coil is placed on the _________ (6), in a pad-like construction linked to the electricity network. The _________ (7) coil is placed on the vehicle, ideally on the bottom of the car, at safe distance from the passengers. The _________ (8) power is rectified to DC and then converted to a high frequency AC power using an DC/AC inverter within the _________ (9), then this high frequency power is transferred to the EV side by induction.

Question 3

Battery swap approach has seemingly quite some advantages over other charging technology, but to get market acceptance is a challenge. Considering that, state if below statements are **true** or **false**.

a. Requirement of standardized battery interface across multiple car manufacturers._________
b. Fool proof way of state of health estimation is important for monetizing battery usage. _________

4.2 AC charging of EVs

In this lecture, we are going to learn about four topics: What are key parts of an AC charger? How does AC charging work? What are types of connectors used for AC charging? How can the AC charging power be calculated?

Let us first look at the parts of an AC charger in Figure 4.5. In its simplest form, AC charging uses an onboard charger to convert AC power from the conventional AC grid to direct current or DC power to charge the traction battery. Cars have a standardised vehicle inlet and a charging cable is used for connecting the vehicle connector to the infrastructure socket of the AC charging station. In some cases, the charging cable is permanently connected to the charging station as well, similar to a petrol pump. For a safe and reliable charging process, there should be several essential components in an AC charging station. Let's look at it by following the power flow from the charger to the EV.

When the charging station and the EV are first connected, the charge controller in the station communicates with the EV. Information regarding the connectivity, fault condition and current limits are exchanged between the charger and the EV. Safety interlocks are used to ensure a safe charging process and to stop the charging in the event of a fault condition or an improper connection between the EV and the charger. When the AC power is provided to the EV, the onboard charger has a rectifier that converts the AC power to DC power.

Then, the power control unit appropriately adjusts the voltage and current of a DC/DC converter to control the charging power delivered to the battery. The power control unit, in turn, gets inputs from the Battery Management System or the BMS for controlling the battery charging. The BMS monitors the key battery operating parameters like voltage, current, temperature. It then provides inputs to the power control unit to control the charging power delivered by the DC/DC converter. Additionally, there is a protection circuit inside the onboard charger. The BMS triggers the protection circuits if the battery's operating limits are exceeded, isolating the battery if needed. This is shown in Figure 4.6.

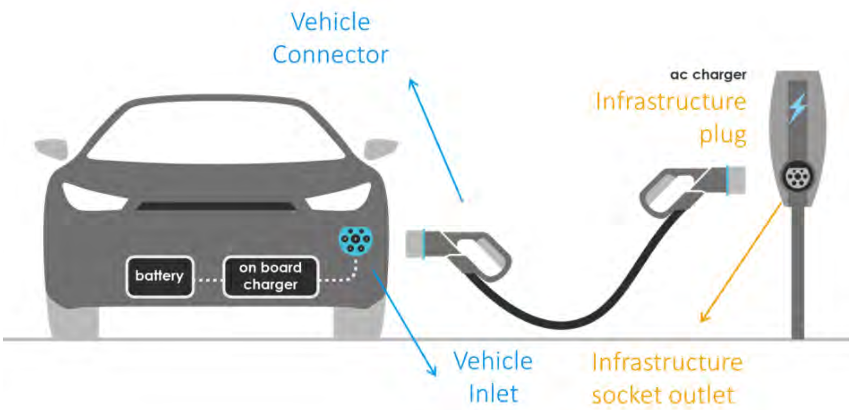


Figure 4.5 AC charger infrastructure schematic

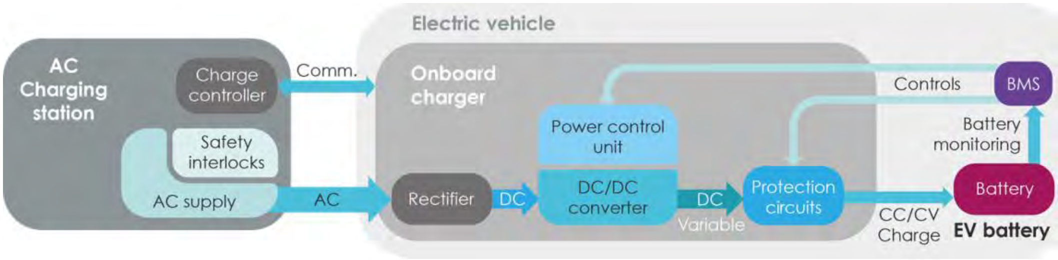


Figure 4.6 Basic AC charging configurations

With a basic understanding of the AC charging process, let us now look at the four main types of AC charging connectors. The EV industry has not agreed on one specific AC connector, so depending on the car brand and country, the connector varies in shape, size and pin configuration. One of the main reasons is the difference in AC voltage and frequency. For example, in the USA, power is supplied using 120V, 60 Hz single phase AC or 240V, 60Hz, dual phase AC. On the other hand, in Europe, 230V, 50Hz single phase AC or 400V, 50 Hz three-phase AC is used. This naturally leads to differences in chargers between the two regions. Generally, an AC connector has two or larger pins to transmit power and some smaller pins for communication. In Figure 4.7 we can see the four types of AC connectors used worldwide, namely:

- The Type 1 connector, which is mostly used in USA & Japan;
- The Type 2 connector, which is mostly used in Europe, including those of Tesla cars;
- The Type 3 connector, used in Europe but is being increasingly phased out by Type 2 connectors
- And finally, the proprietary connector used by Tesla for its cars in the USA

Besides this, China has its own standard for AC charging, which is similar to Type 2 connectors.

Figure 4.7 AC charger types: an overview

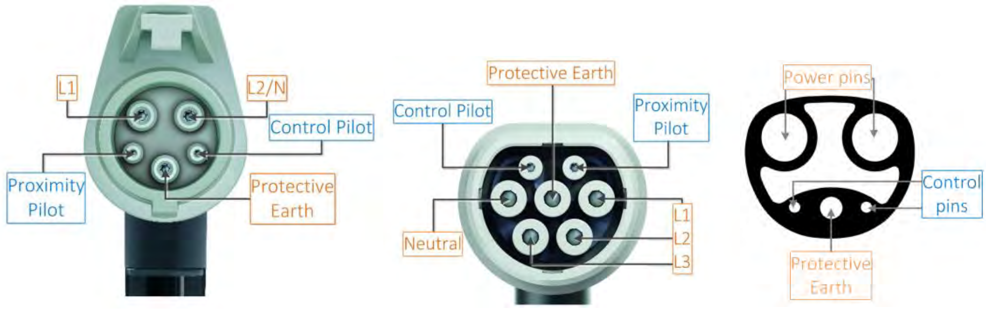


Figure 4.8 AC connectors: Type 1 (on the left), Type 2 (in the centre) and Tesla US connector (on the right)

Let us now look at these connectors in detail. In Figure 4.8, on the left, we show a Type 1 vehicle connector, which is used specifically for charging with single-phase AC. It has a round housing consisting of five pins. 2 AC pins: L1, L2 for single-phase AC; a pin for the protective earth; and two signal pins namely, the Proximity Pilot (PP), and the Control Pilot (CP). The proximity pilot is used for ensuring connectivity between the EV and the charger, and the control pilot is used for controlling the charging current. The maximum voltage and current rating of this charger are: 120 V or 240V single-phase AC with a current up to 80A

Next let us look in Figure 4.9 at the Type 2 vehicle connector, which is also called the Mennekes connector. The Type 2 connector is circular in shape, with a flat top edge. The top row consists of two small pins for communication, namely the proximity pilot and the control pilot. The middle and lower row consists of five for AC power transfer, namely three pins for three-phase AC connection and two pins for the neutral and protective earth. The maximum voltage/current rating are : 1 phase 230V up to 80A and 3 phase 400V up to 63A.

In case of Tesla, they use a proprietary connector in the US, as shown in this picture. In Europe, Tesla cars use the Type 2 connector. Unlike other car manufacturers, Tesla uses the same connector for both AC and DC charging. With this AC connector, a maximum charging power 17.2 KW is possible from a 240V AC outlet.

You may have noticed that the Type 1 and Type 2 connectors have 2 common communication pins: the Control Pilot (CP) and the Proximity Pilot (PP). Let us look deeper into their function. The Proximity Pilot (PP) checks if the vehicle connector is connected properly to the vehicle inlet. If the connection is not properly established, the Proximity Pilot will detect

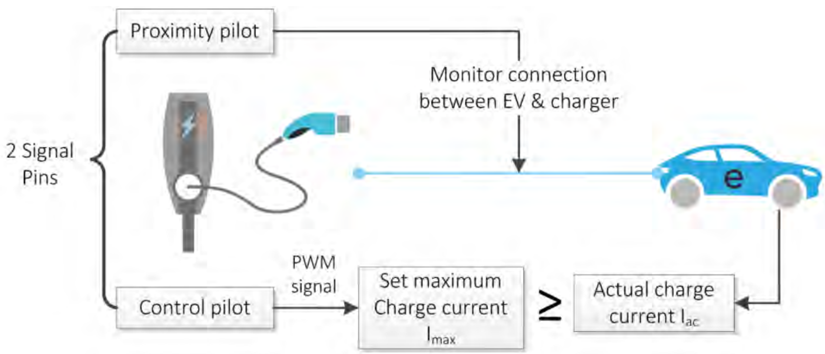


Figure 4.9 AC charging: Type 1 and Type 2 PP and CP schemes

it, and the entire process will be disabled for safety. The second special pin is the control pilot (CP), and it is used for controlling the charging current. The control pilot continuously sends a pulse width modulated or PWM signal to the car. In this way, it tells the car the maximum current that can be drawn from the charging station, I_{max}. The car then can draw the desired current I_{ac}, as long as this value is smaller than the maximum current I_{max}.

Finally, let us look at how we can calculate the AC charging power. The calculation of single phase AC charger power is the product of the single-phase AC voltage V_{ac}, and the grid current I_{ac}:

$$P_{ch}=V_{ac}\cdot I_{ac} \tag{3.1}$$

The three-phase AC charging power is calculated as root three times the product of the line to line three-phase AC voltage V_{3ac} and the grid current I_{ac}:

$$P_{ch}=\sqrt{3}(V_{3ac}I_{ac}) \tag{3.2}$$

For AC power calculations, the root mean square or the RMS values of the voltage and currents are used. Keep in mind that not all the power is delivered to the traction battery due to losses in the charging system. Typically on-board charger has 90-95% efficiency.

Based on the AC charging power that has been introduced, now let's look at the charging time versus charging power for different battery sizes. Assuming no losses, the charging time t_{ch} can be calculated as the battery capacity E_{batt} divided by the charging power P_{ch}:

$$t_{ch}=\frac{E_{batt}}{P_{ch}} \tag{3.3}$$

The graph in Figure 4.10 shows the required charging time of different charging powers, which used to charge two batteries with a size of 30kWh and 100kWh.

The data labels shown are commonly used EV AC charging powers. As we can see, even if we charge a battery with higher powers, say 22kW, a couple of hours are still required to charge the battery fully. Considering there are limited space and weight for the on-board charger in the car, there is an upper limit for the maximum AC charging power. This is why we need to move too fast charging of 50kW and above using DC off-board chargers.

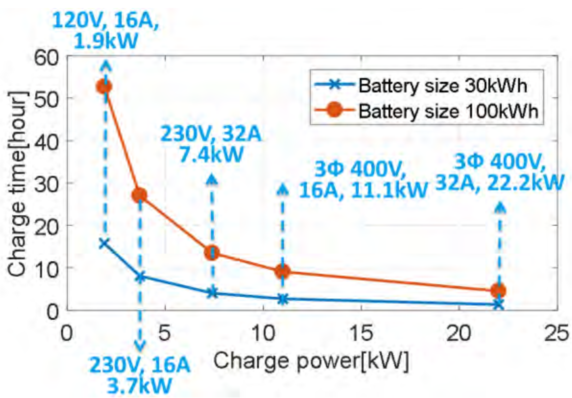


Figure 4.10 Charging time and charging power

To wrap up, you have now got an idea about the parts of an AC charger and the four AC charger connector types. We also looked at the role of the proximity and control pilot in control of the charging. Finally, we saw how a simple formula could be used to estimate the charging power and charging time for AC charging.

Practice problems

Question 1

The PWM pulse on the control pilot on the Type 1 and Type 2 chargers are used to:

- *Control the charging voltage*
- *Control the charging current correct*
- *Check for the proper connection between EV and charger*
- *Check the isolation monitoring of the battery*

Question 2

An EV consumes 100Wh/km and is required to go on a trip of 300 km trip. What must be the AC current drawn from a single phase 230V AC charger so that the car can be fully charged in 5h from an empty battery?

- 20.4 A
- 26.1 A
- 15.4 A
- 30.6 A

Question 3

Newmotion is the largest EV charging service providers in Europe. In this link, you can find the datasheet of one of their AC EV charging points that are designed for use in commercial locations. Kindly open and review the datasheet of their 'Business Lite' EV charger to answer the following question.

a. What is the type of the charger used?
   - Type 1
   - Type 2
   - Chademo
   - Combo

b. Does the charger facilitate three-phase charging?
   - Yes, 400 V three phase
   - Yes, 110 V three phase
   - No

c. What are the maximum charging power and current of the charger?
   - 22kW, 16A
   - 11kW, 16A
   - 22kW, 32A
   - 11kW, 32A

4.3 DC charging of EVs

In this lecture, we are going to learn about three things: What are the key parts of a DC charger? What types of connectors are used for DC charging? And what are the limitations of DC fast charging?

First of all, let's have a look at what are the key parts of a DC charger. DC Fast Chargers typically operate at Level 3 charging power and are designed to charge electric vehicles quickly with an electric output ranging between 50kW – 350kW. With high power operation, the AC/DC converter, the DC/DC converter and the power control circuits become larger and more expensive. That is why DC fast chargers, in Figure 4.11, are implemented as an off-board charger rather than as an on-board charger so that it does not take up space within the vehicle and the fast charger can be shared by many users.

Let us now analyse from Figure 4.12 the power flow for DC charging from the DC charger to the EV battery. In the first step, the alternating current or AC power provided by the AC grid is first converted into direct current or DC power using a rectifier inside the DC charging station. Then, the power control unit appropriately adjusts the voltage and current of a DC/DC converter to control the variable DC power delivered to charge the battery. There are safety interlock and protection circuits used to de-energize the EV connector and to stop the charging process whenever there is a fault condition or an improper connection between the EV and the charger. The battery management system or BMS plays the key role in communicating with the charging station to control the voltage and current delivered to the battery and to operate the protection circuits in case of an unsafe situation. For example, Controller Area Network (shortly referred to as CAN) or Power line communication (shortly referred to as PLC) is used for the communication between the EV and the charger.

Now that you have a basic idea of how a DC charger is configured, then let us look at the main DC charging connector types. In Figure 4.13 we can see that there are five types of DC charging connectors used globally: the CCS-combo 1, which is mainly used in the US; the CCS-combo 2, which is mainly used in Europe; the CHAdeMO connector, used globally for cars

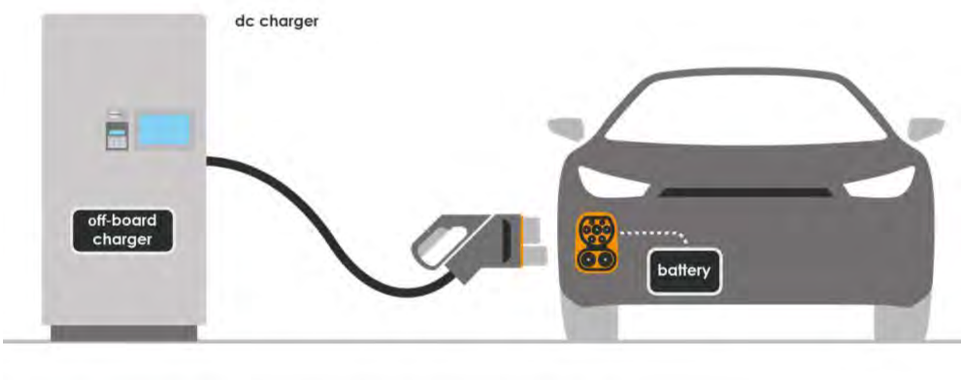


Figure 4.11 DC charging off-board infrastructure

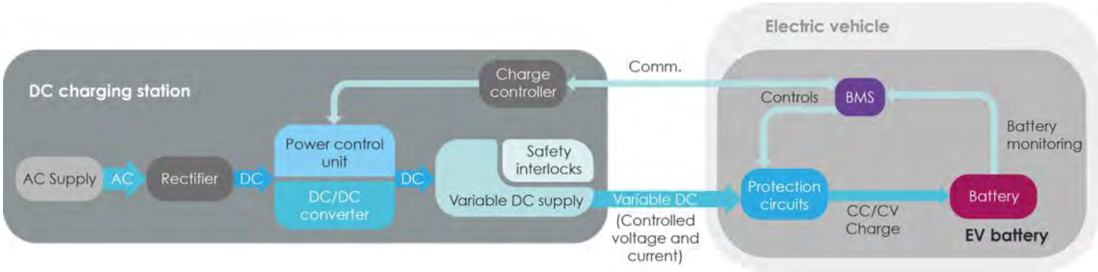


Figure 4.12 Off-board DC charger scheme

Figure 4.13 DC charger types: an overview

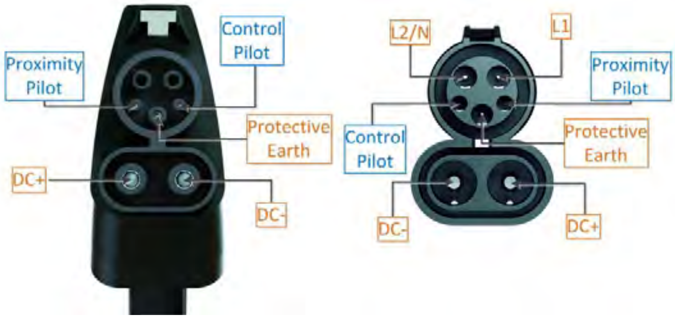


Figure 4.14 DC charger CCS/Combo 1

built by Japanese automakers; the Tesla DC connectors, which are used for AC charging as well; and finally, China has their own DC connector, based on the Chinese GB/T standard.

Let us now look at them one by one. The combined charging system or CCS connectors, also referred to as Combo are integrated connectors for both AC and DC charging. They are derived from the Type 1 and Type 2 AC charging connectors by adding two big extra pins for high current DC charging. The connectors are respectively called Combo 1 and Combo 2.

Let us first look at the CCS Combo 1 connector. In Figure 4.14 the Combo 1 vehicle connector is shown on the left side, and the vehicle inlet is shown on the right side. The vehicle connector of Combo 1 is derived from the AC type 1 connector and retains the earth pin and the two

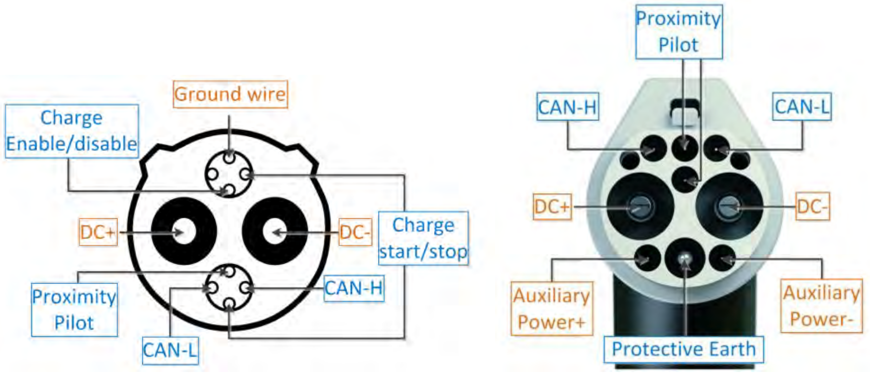


Figure 4.16 DC charger CHAdeMO (on the left) and China GB/T standard (on the right)

signal pins namely, the control pilot and the proximity pilot. In addition, two DC power pins are added for fast charging. On the vehicle inlet, the pin configuration in the upper part is the same as AC Type 1 connector for AC charging while bottom two pins are used for DC charging.

Similarly, the CCS Combo 2 connectors (in Figure 4.15) are derived from the AC Type 2 connector and retain the earth pin and the two signal pins namely, the control pilot and the proximity pilot. Two DC power pins are added at the bottom for high power DC charging. Similarly, on the vehicle inlet side, the upper part facilitates three-phase AC charging like the Type 2 connector and the bottom two pins are used for DC charging.

Unlike Type 1 and Type 2 connectors that uses only pulse width modulation or PWM signalling on the control pilot, power line communication is used in both Combo 1 and Combo 2 chargers on the control pilot. PLC is a technology that carries data for communication on existing electric power lines which is used simultaneously for power transmission as well. The CCS charger can deliver up to 350 A at a voltage of between 200 V to 1000 V giving a maximum power output of 350 kW. It must be kept in mind that these values are continuously updated to cater to the voltages and power requirements of new electric cars.

The third DC charger type is CHAdeMO, which is a Type 4 EV connector and has three power pins and six signal pins. CHAdeMO uses the Controller Area Network or CAN protocol in the communication pins for signalling. This is depicted in Figure 4.16. A Controller Area Network communication is a robust vehicle communication standard designed to allow

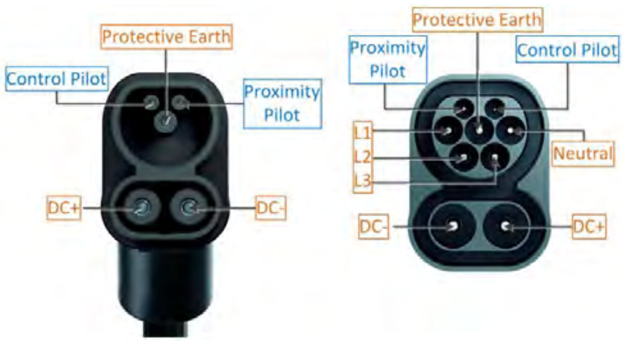


Figure 4.15 DC charger CCS/Combo 2

microcontrollers and devices to communicate with each other in real-time without a host computer. As of now, the voltage, current and power levels of chademo are 50-500 V, up to 400 A, thus providing a peak power of 200 kW. In the future, it is expected that EV charging up to 1000 V and 400 kW will be facilitated.

China has their own DC charging standard and connector that uses CAN bus for communication, which is shown also in Figure 4.16. It has five power pins, two for DC power, two for low voltage auxiliary power, and one for ground. This charger has four signal pins, two are for proximity pilot and two for CAN communication. As of now, the nominal voltage is 750 V or 1000 V, and the current up to 250A is supported by this charger.

Finally, in the case of Tesla, Tesla superchargers in the US use their own proprietary charging connector, while the European variant uses the Type 2 Mennekes connector, but with DC charging built in. The unique aspect of the Tesla connector is that same connector and pins are used for both AC and DC charging. Tesla now offers DC charging up to 120kW and this is expected to increase in the future. Tesla chargers are shown in Figure 4.17.

As you can see the fast charging is quite attractive in the sense of high power charging with short charging times. But the fast charging power cannot be increased infinitely. That is due to three technical limitations.

First of all, higher charging current leads to higher overall losses both in the charger and in the battery. For example, if the internal resistance of a battery is R, the losses in the battery can be expressed as I^2R, for simplicity, where I is the charging current. So the losses increase by four times when the charging current is doubled. As the charging currents increases, the effective capacity of the battery decreases as well (for example, as given by Peukert's law).

The second limitation is from the battery. When fast charging a battery, the SOC of the battery can only achieve 70-80%. This is because fast-charging creates a lag between the voltage and state-of-charge and this phenomenon increases as the battery is being charged faster. Hence, fast charging is typically done in the constant current or CC region of the battery charging and after that, the charging power is reduced in the constant voltage or CV charging. Moreover, the battery C-rate increases with fast charging and this reduces the battery lifetime.

The third limitation is from the charging cable. For any EV charger, it is important that the cable is flexible and lightweight for people to use and connect it to the car. With higher charging power, thicker cables are needed to allow more charging current, else it will heat up

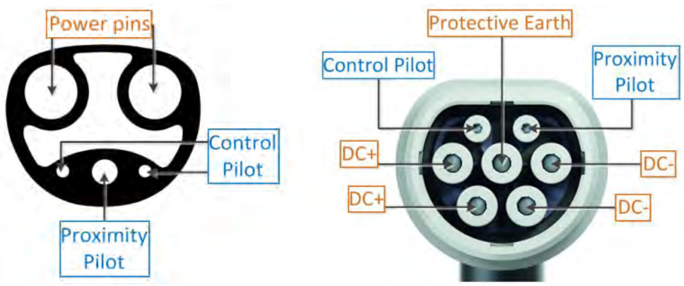


Figure 4.17 DC charger Tesla Type 2 in Europe (on the left) and proprietary connector in USA (on the right)

due to the losses. DC fast charging systems today can already transmit charging currents of up to 250 A without cooling. However, in the future with current above 250 A, the charging cables would become heavy and less flexible to use. The solution would be to use thinner cables with cooling and thermal management to ensure that cables do not heat up. This is, of course, more complex and costly than using a cable without cooling.

List of EV Charging standards

- IEC 62196-1/IEC 62196-2/IEC 62196-3: Plugs, socket outlets, Vehicle Connectors, Vehicle-Inlets — conductive charging of electric vehicles
    - Part 1: General requirements
    - Part 2: Dimensional compatibility and interchangeability requirements for AC pin and contact-tube accessories
    - Part 3: Dimensional interchangeability requirements for

- IEC61851-1/-21/-22/-23/-24: Electric vehicle conductive charging system
    - Part 1: General requirements
    - Part 21-1: Electric vehicle on-board charger EMC requirements for conductive connection to an AC/DC
    - Part 21-2: EMC requirements for OFF board electric vehicle charging systems (under preparation) supply
    - Part 22: AC electric vehicle charging station (in future merged with 61851-1)
    - Part 23: DC Electric vehicle charging station
    - Part 24: Control communication protocol between off-board DC charger and electric vehicle

- ISO/IEC 15118-1/-2/-3: ISO/IEC 15118 – Road vehicles – Vehicle to grid communication interface
    - Part 1: General information and use-case definition
    - Part 2: Technical protocol description and Open Systems Interconnections (OSI) layer requirements
    - Part 3: Physical layer and Data Link layer requirements

- Chinese GB/T 20234.1/.2/.3: Connection set of conductive charging for electric vehicles
    - Part 1: General requirements
    - Part 2: AC charging coupler
    - Part 3: DC charging coupler

Fast charging networks

Charging an electric car will be a mix of home charging, destination charging (at work, a supermarket, hotels, etc.), public slow charging and public fast charging. In case of fast charging, fast charging networks on a nationwide scale along highways similar to gasoline stations are the next step. This will ensure seamless travel for long distance travel offering charging in less than 30 min. Estonia, for example, was the first country in the world to build a nationwide EV fast charging network. Several initiatives for state-wide and nationwide charging networks have been announced and are in partial/full operation already. A few examples of fast charging networks are:

- Fastned EV charging network, Netherlands
- Tesla supercharging network
- Estonia nationwide charging network
- Ionity Europe fast charging network
- Electrify America
- New Zealand ChargeNet NZ network
- Austrian Smatrics network

While the above list is not exhaustive, learners can get an idea of the what these networks are, how they stations are spread out and located, what type of chargers they facilitate and what are the charging power levels.

Practice problems

Question 1

Match the following charger types and their characteristics.

Charger types:	*Characteristics:*
• Type 1 charger	• Europe
• Type 2 charger	• USA
• CHAdeMO charger	• DC charger used by European EV manufacturers
• COMBO charger	• DC charger originated from Japan

Question 2

Indicate whether the following statements are **true** or **false**.

a. A type 1 charger can be used for three-phase charging at 11kW. __________
b. The CHAdeMO charger is used for single phase AC charging at 230V. __________
c. The Chinese GB/T DC charger has 6 power pins – Two for DC power, two for auxiliary power, one for the protective earth and 1 for neutral. __________
d. A Type 2 charger is used in the USA for charging at 5kW. __________

Question 3

For a long lifetime of the battery, the battery charging is restricted to 1C charging rates for a 50 kWh battery.

a. If the DC charger has a 90% efficiency, what is the maximum charging power drawn by the DC charger from the grid to just reach the C-rate limit of the EV battery?
   - o 45.5 kW
   - o 55.5 kW
   - o 4.5 kW
   - o 5.5 kW

b. An EV with a 50 kWh battery rated at 500V is charged at 100 kW. What is the C-rate of the battery pack for charging?
   - o 2C
   - o 3C
   - o 5C
   - o 0.2C

4.4 Smart charging and V2G

The following questions will be explained in this lecture: What is smart charging and vehicle-to-grid and why we do we smart charging? What are the advantages and disadvantages of vehicle-to-grid? And finally, in which cases can smart charging be applied?

Smart charging is defined as a series of intelligent functionalities to control the EV charging power in order to create a flexible, sustainable, low cost and efficient charging environment. It has several benefits and has a huge potential for the future. For example, smart charging can increase the flexibility of charging by controlling the charging power, charging time duration and charging power flow direction. With the high charging flexibility, the utilization rates of fixed assets like transformers and power lines can be higher, which also helps in reducing the cost of EV charging. Smart charging can increase the efficiency of power transfer and help reduce the peak demand on the distribution network. Further, EVs can be made more sustainable by charging them based on solar and wind generation. Moreover, it can provide new revenue streams to EV owners like providing frequency regulation and vehicle-to-grid services.

Vehicle-to-grid refers to the concept of using the electric vehicle battery to feed power back to the grid. In order to facilitate vehicle-to-grid, we need bidirectional electric vehicle chargers that both draw and feed power between the EV battery and the grid. Besides the grid, the battery power can flow from the vehicle to a home, to a building, to a load, etc. and it is called V2H, V2B, V2L, respectively. V2X is the generic term that is used to include all such applications.

There are a number of key benefits of V2X technology. First of all, it enables the storage of electricity in the car, especially from renewable sources which lead to emission reductions. Also, by using the stored energy, the peak demand in the electrical grid can be reduced. Next to that, electric cars can now serve as an essential system component in an emergency power supply. Lastly, ancillary services can be offered to the grid using an electric car with V2X configuration providing a revenue stream to the EV user.

At the same time, a number of main challenges for V2X are identified as well. First, V2X needs bidirectional chargers, which are bigger and more costly than unidirectional chargers. Second, the lifetime of the battery inside the EV is partially reduced, since the bi-directional charging demands more charging cycles, causing additional degradation. Further, the ICT infrastructure, the required standardization and regulatory framework and financial incentives which are essential for the implementation of V2X are still under development. Finally, it is important to note that vehicle-to-grid is currently not possible using AC chargers due to technological limitations. This is because a bidirectional on-board charger is needed for vehicle-to-grid, but most current EVs only have a unidirectional on-board charger. Further, V2X requires higher levels of communication between the EV and charger and this is not fulfilled by the simple PWM communication in Type 1 and Type 2 AC chargers. Hence, bidirectional off-board DC chargers are used for vehicle-to-grid applications using a higher level of communication between the EV and charger using PLC, power line communication or CAN, control area network communication. With a basic understanding of smart charging and vehicle-to-grid, let us now look at a few examples to understand the application. First, smart charging can help in balancing the local load, and this can be done in two ways: shift the charging time slot according to the loading on the grid, or by balancing multiple charge points with priority. Second, smart charging can increase the utilization and subsequently the installation of renewable energy in the grid. Third, smart charging can facilitate charging based on the electricity prices in order to reduce the charging cost. Apart from that, the smart charging can be applied to peak shaving and to provide backup services for the grid. The last three examples are specifically applicable to vehicle-to-grid. Let us now look at the smart charging applications one by one.

The first load balancing approach is to shift the charging time slot and to adjust the charging power based on the grid capacity and local loading condition, as shown in Figure 4.18.

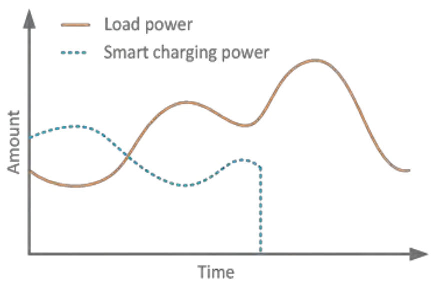


Figure 4.18 Load balancing: adjust time and power according to load

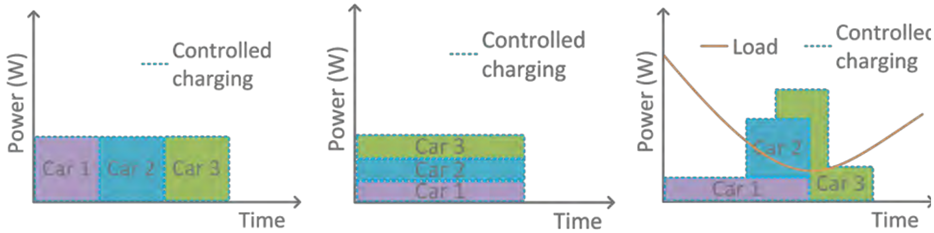


Figure 4.19 Load balancing: multiple charge points with priority

For example, when the load on the grid is low, the EV charging power can be increased. Alternatively, if the load power increases, then the EV charging power can be subsequently reduced. Finally, the EV charging can be stopped if the grid is overloaded and remain so until the load power is back to normal. With a limited maximum power for charging the cars, smart charging can sequentially operate multiple charge points with priority, or adjust the power of each charging point so as to be within the maximum limit.

With the smart charging, each car can also be charged with different strategies according to the load and the priority, for instance like shown in Figure 4.19. Smart charging can help in controlling the charging power of the car based on renewable energy production, say from solar and wind generators.

Further, with V2G, the electric cars can be used as massive energy storage to balance the variable generation from renewable energy sources, like in the example depicted in the graph of Figure 4.20 on the left.

Next, we look at price-based smart charging in the graph in Figure 4.20 on the right. Here, the charging power is increased when the electricity price is low, and the charging power is decreased or even stopped when the electricity price is high. Further, customers can get more profit when V2x is applied. For example, we can charge the cars when the electricity is cheap and discharge the car via V2x when electricity is expensive and above a certain pricing level. In this case, the "x" of the "V2x" can be home, building or the grid.

In case of peak shaving (see Figure 4.21), the aggregated EVs can work as mass storage in the grid. With controlled charging, the EVs can be charged when there is extra renewable energy generation, and they can discharge via V2G to feed the grid when is a peak load in the evening. By doing so, the peak of both generation and consumption can be shifted, and the electric

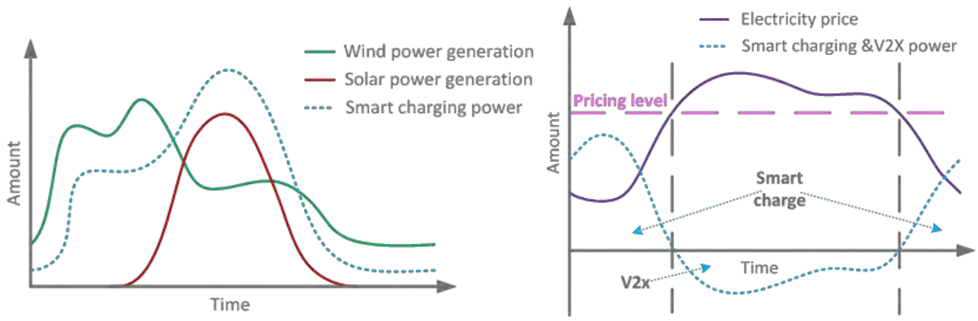


Figure 4.20 Renewable energy availability (on the left) and price-based (on the right) smart charging strategies

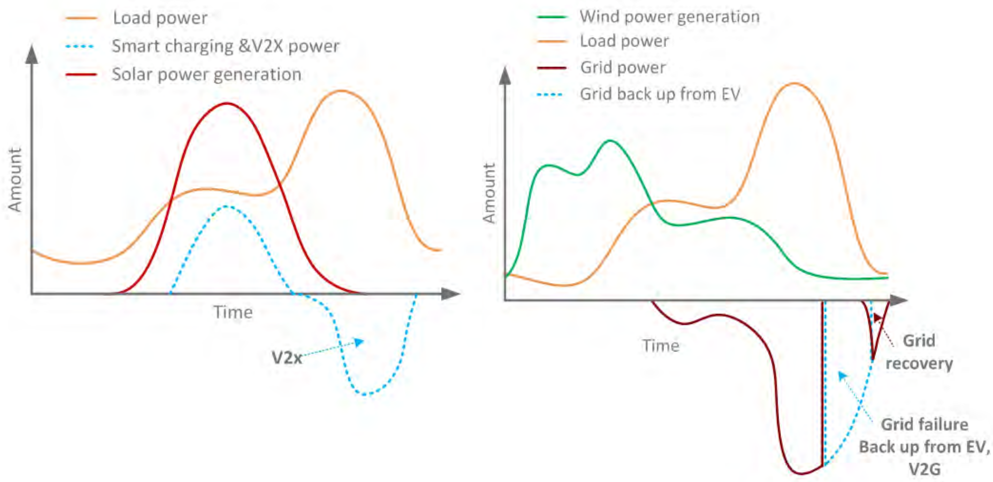


Figure 4.21 Peak shaving (on the left) and grid backup (on the right) smart charging strategies

power demand-supply gap can be perfectly matched. In the future, electric vehicles will even be able to operate as a backup for the grid on a relatively large scale. In case of a short duration failure, EVs can be connected to the grid, to our homes or to loads and can be controlled to provide emergency power via V2G.

To wrap up, you have now got an idea of what is smart charging and the key role it can play in future smart grids. Vehicle-to-grid is a special case of smart charging where the energy from the EV battery can be used to feed power to homes, buildings and to the grid. We looked at some examples of smart charging to see how the EV charging can be controlled based on renewable generation, energy prices, grid loading and how the EV can be used as a storage and as an emergency power supply.

4.5 ICT protocols for charging

Charging electric cars is part of an evolving ecosystem with many different machines and stakeholders that must be able to exchange information automatically. In this video, I will explain how you can use a range of computer protocols to do just that.

Before I started my second career in renewable energy and electric vehicles, I was leading Telecom projects where we rolled out the first mobile phones. I find the lessons I learned there very applicable to the world of charging infrastructure. Now everybody takes it for granted that you only need a contract with one service provider. That this makes sure your phone works everywhere. And that you simply get one bill at the end of the month. But creating that system was far from trivial, and with charging infrastructure we have not yet reached a similar level of maturity. For example, in the Netherlands you can use almost any public charge point using the same RFID card but once you cross the border things are highly fragmented. I think the situation we should be striving for is the same as the one we take for granted when we use mobile phones. Your car should be able to automatically authenticate you on any network so you can simply plug-in and charge everywhere, without excessive roaming charges and with one simple bill at the end of the month.

The key to making that happen is open standards, just like we have on the Internet. Such open standards enable competition by avoiding lock-in and enabling new entrants, thus stimulating innovation. These standards connect two of the oldest and largest industries on earth. Currently, these giants have not yet woken from their slumber. So just as with the Internet, we have to be quick and then we can still get it right. Such standards do not dictate business models, roles ore functionalities but rather enable innovation by enabling communication between all parties involved.

Let's start with the simple case of EV charging at home. And let's assume that you have a dedicated charger that is managed by a remote operator. For this you need an EV manufacturer - the OEM - the EV itself and a charging station, also referred to as an EVSE. In order for the EV to talk to the charger, the IEC 61851 protocol is often used. The new functionality will become available when the ISO 15118 protocol is deployed. Thinks like authentication and smart charging (even giving energy back to the grid) that is automatically handled by the car. Perhaps this looks simple, but to enable this scenario in practice, the charging station should have the option to be remotely "controlled" by an operator. Let me give you some functions for which this is necessary: metering EV electricity usage. This is often useful to get tax or company money back. Remote troubleshooting of the charging process. And firmware updates for fixing bugs or adding functionality. This makes the picture a bit more complex because we need to add the so-called Charge Point Operator. The de-facto open standard for this is OCPP which stands for Open Charge Point Protocol.

Now let's make it a little bit more complex: the user is not charging at home but at a public charging station. This is shown in Figure 4.22. Here we run into the problem that we have different operators for different charging stations. To get one bill at the end of the month, you will need an ID, currently usually a charging card. This is provided by a party that is referred to as the E-Mobility Service Provider, the EMSP. To be able to use your charging card at any charging station of any operator, some form of communication between the EMSP and the CPO, is necessary. This communication is for authorization purposes and includes the handover of billing data from any CSO to the EMSP to be able to provide one bill to the EV

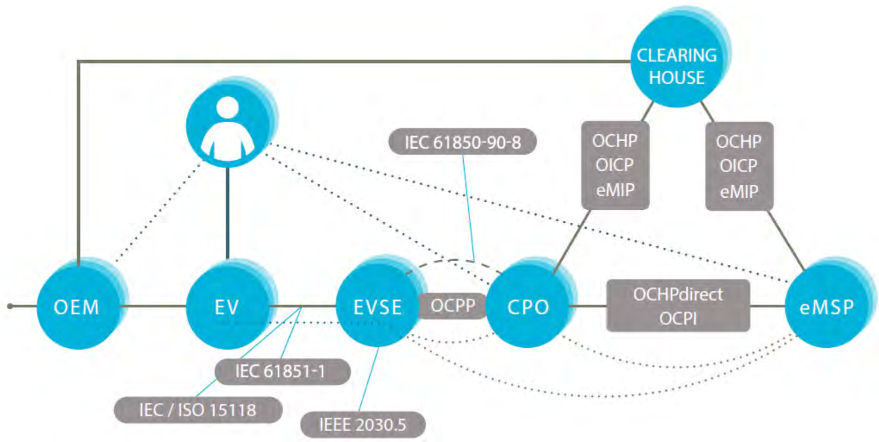


Figure 4.22 Public EV charging ICT infrastructure

user. If you want to enable roaming to other networks, and you are not using peer-to-peer or distributed ledger technology, you will also need a clearinghouse.

Figure 4.23 shows different ways to facilitate roaming. The reference document provided with this course provides a step-by-step walkthrough for all the different scenarios. As you can see there are different protocols available and you have the choice to do it with and without clearinghouse. An add-on not mentioned here yet is reserving a charge point in advance, so you know it will be available. To be able to do this, information about charging stations should be available. This implies providing more information about the charge point and of course also the tariff and availability. It's an example of information that can be supplied using roaming protocols but it is not yet widely used. The most extensive example I want to give is smart charging which will become the norm once we move to smart grids.

Smart charging means that you do not automatically charge as quick as possible and as fast as possible. Instead you take more factors into account. For a customer, this means charging when the price is lowest. For the power system, it means charging when the network is not overloaded. For society, it means using renewable energy in the best way possible. Since cars have big batteries and use a lot of energy, but are also standing still 23 hours per day – on average – smart charging offers tremendous potential. My *SparkCity* model shows that in the Netherlands, if we apply vehicle to grid and more than 20% of the cars are electric and engaged in smart charging, all daily mismatch between supply and demand can be eliminated. This is even true if all energy comes from solar panels and windmills. Of course I'm not talking about eliminating seasonal fluctuations, but on a daily basis, the power of electric vehicles to stabilize the grid is enormous. More information can be found in [1].

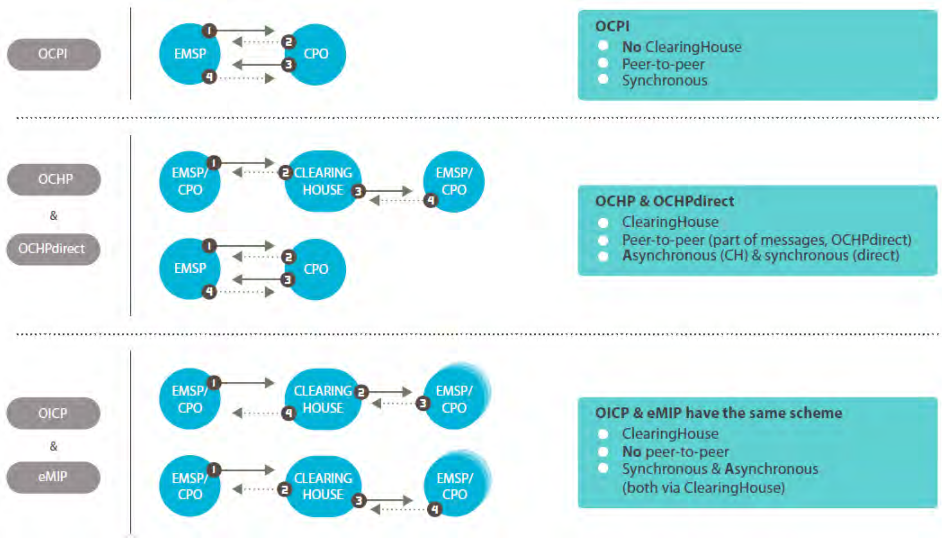


Figure 4.23 Example: comparing four existing roaming protocols

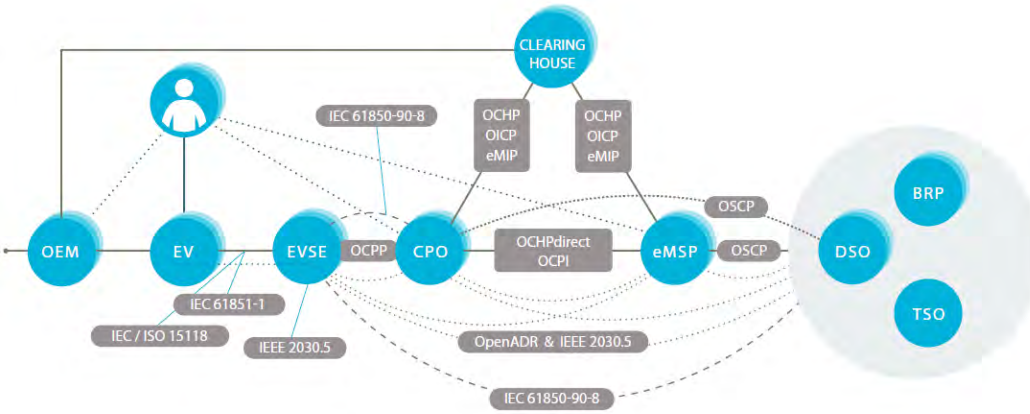


Figure 4.24 ICT infrastructure for smart charging

With smart charging, the stakeholders on the electricity grid come into full play [2]. Take a look at Figure 4.24. The DSO, or distributed system operator, that provides local electricity and has to watch out for voltage and local grid congestion. The TSO, or transmission system operator, that transports electricity over larger distances and has to watch out for the frequency and for grid congestion over larger areas. The BRP or balance responsible party is the legal role that encompasses all the bidding that goes on to balance supply and demand on the electricity market. The protocols for smart charging are not yet completely clear but many developments are taking place. I recently wrote a paper about the excellent synergy between OCPP and OpenADR. In effect, the Utilities could use their OpenADR infrastructure and by connecting it to OCPP enabled charge point they could technically start smart charging all connected vehicles. IEEE 2030.5 is another interesting protocol that is primarily aimed at in-house smart grid solutions. A comparison of the different protocols we discussed based on their functionality is given in Table 4.1.

However, smart charging is not yet common practice and currently, protocols have limited support for it. OCPP 2.0 is fully smart charging enabled but only a few implementations exist where the actual state of charge and time of departure are used from the EV user. One issue

Table 4.1 Protocol comparison: functionality

	OSCP	OpenADR	OCPI v0.4	IEEE 2030.5	OCPP	61850-90-8	OCHP	OCPI 2.1	OICP	eMIP	IEC 61851	ISO 15118
PROTOCOL	**SMART CHARGING**				**CS <> CP**		**ROAMING**				**EV <> CP**	
Authorize charging session			•		•		•	•	•	•		•
Billing					•		•	•	•	•		
EV Charging											•	•
Handle registration		•		•				•				
Manage grid	•	•		•	•	•						
Operate Charge Point					•	•						
Provide charge point information			•				•	•	•	•		
Reservation			•		•		•	•	•			•
Roaming			•				•	•	•	•		
Smart Charging	•	•	•	•	•	•	•			•	•	•

is that most EVs don't communicate their state of charge to the charge point. Another one is that users do not provide their time of departure, although it can often be predicted. Furthermore, renewable energy aspects are not yet taken into account in protocols and functionality. But as the adoption of electric vehicles grows, and as the adoption of distributed and intermittent energy sources like solar and wind grows, so will the importance of smart charging grow.

Table 4.2 summarizes the maturity, market adoption, interoperability and openness of the protocols. Just to give two examples: OCPP can only be used for the communication between charge point and charge point operator but scores high on maturity, interoperability, market adoption, openness and testing tooling but official certification is still missing. And by the way, version 2.0 is already available. OCPI can be used both for smart charging and for roaming but in the latter capacity, it has more to offer.

There are a lot of protocols that are in use, and both protocol specifications and their applications are still emerging. Nevertheless, I hope I have given you a very general overview of the functionalities, stakeholders and protocols that can be used as building blocks for a thriving charging infrastructure industry. Smart charging is something that will be increasingly important as more electric vehicles become available and as the use of intermittent and distributed sources of renewable energy growth. It has advantages for consumers, stakeholders regarding the electricity grid and for society as a whole. Open protocols will be crucial for the development of the charging infrastructure market. But those who know the history of the Internet, also know that creating an innovative and thriving ecosystem through the use of open standards is not a given but something that requires vigilance and the occasional hard fight.

Table 4.2 Protocol comparison: non-functional

	Version	Maturity	Interoperability	Market Adoption	Openness	Testing tool (dedicated / specific)	Certification (official testlab)
SMART CHARGING							
OSCP	1.0	Low	High	Low	Medium	No	No
OpenADR 2.0	1.1	High	Medium / High	Medium / High	High	Yes	Yes
OCPI	v0.4	Very low	Very low	Low	Low	No	No
IEEE 2030.5	2.0	High	Medium / High	Low	High	Yes	Yes
CS – CP							
OCPP	1.6	High	High	High	High	Yes	No
IEC 61850(90-8)	-	Medium	Low	Low	High	Unknown	Yes
ROAMING							
OCHP	1.4	High	High	Medium / High	Medium	No	No
OCPI	2.1	Low	High	Low	High	No	No
OICP	2.1	High	High	High	Medium	No	No
eMIP	0.7.4	High	High	Medium	Low / Medium	No	No
EV – CP							
IEC 61851-1	-	High	High	High	High	Unknown	Yes
ISO / IEC 15118	-	Medium	High	Low	High	No	No

Practice problems

Question 1

Choose the right option from the following EV charging topics: **Type 1 connector**, **Type 2 connector**, **Fast charging**, **DC charging**.

- CHAdeMO. ________________
- Level 3 charging. ________________
- PWM on control pilot. ________________
- Three-phase AC charging. ________________

Question 17

In a city, the grid electricity prices are split over the day into three different tariffs based on time of the day:

- 00:00h to 08:00h with 10 cents/kWh,
- 08:00h to 16:00h with 15 cents/kWh,
- 16:00h to 24:00h with 20 cents/kWh.

An EV requires 100 kWh of energy and is connected to a DC charger that operates at 80% efficiency (Hence 125 kWh of energy is drawn from the grid). The EV charger operates at fixed input power of 10kW but can be smartly turned on and off based on the prices.

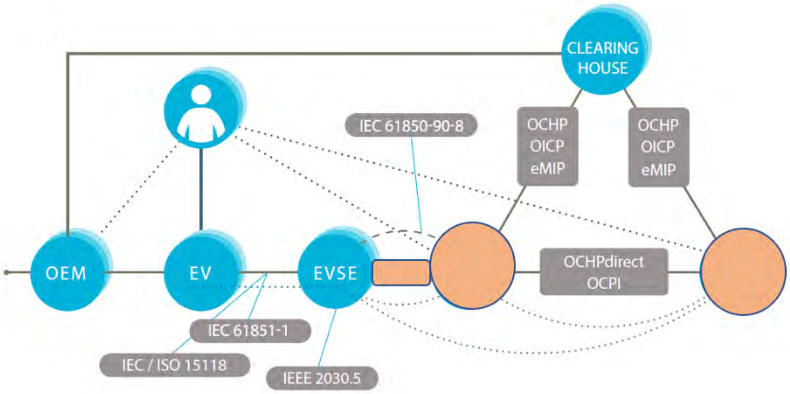
a. What is the best times to charge the car in the day to have the lowest charging cost?
   - 8h between 00.00 - 08.00 and 4.5h between 16.00 - 24.00
   - 8h between 00.00 - 08.00 and 2.5h between 08.00 - 16.00
   - 8h between 00.00 - 08.00 and 2h between 08.00 - 16.00
   - 8h between 00.00 - 08.00 and 4.5h between 08.00 - 16.00

b. What is the corresponding charging cost that needs to be paid to the grid for drawing 125 kWh?
   - $30.15
   - $14.75
   - $20.55
   - $45.5

c. Let us assume that the car is charged at the worst times in the day (when the energy prices are high) that results in the highest charging cost. By what factor is the charging cost higher when compared to the previous case?
   - 1.5 times higher
   - 3 times higher
   - Same cost
   - 2 times higher

Question 2

a. Write into the orange circles and complete the public charging EV network, choosing from: **CPO**, **EMSP**, **OCPP**.



b. What does the OCPP stand for?
- o Open Charge Point Protocol
- o Open Charge Protocol Point
- o Open Control Point Protocol

c. Complete the following paragraph by choosing the right options from the below pool.

Electric Mobility Service Point, **Charging Point Operator**, **public**, **different**, **EMSP**, **communication**.

EMSP stands for ________________(1). In a ________________ (2) charging station, we run into the problem that we have different operators for ________________ (3) charging stations. To get one bill at the end of the month, you will need an id, currently usually a charging card. This is provided by a party that is referred to as the ________________ (4). To be able to use your charging card at any charging station of any operator, some form of ________________ (5) between the Electric Mobility Service Provider and the ________________ (6), is necessary.

Question 3

State if the following statements are **true** or **false** with respect to smart charging:

a. There is no single uniformly accepted communication standard yet for smart charging.

____

b. The DSO or distribution system operator that provides local electricity must watch out for voltage and local grid congestion. _________

c. The TSO or transmission system operator that transports electricity over larger distances must watch out for the frequency and for grid congestion over larger areas. _________

4.6 Case Study: ABB

ABB is an all-round technology company that specialises in electrification, robotics, industrial automation and power grids. They were one of the first companies to become involved in the development of charging infrastructure for electric mobility. They deliver a range of services. Individuals and companies can use their compact AC wall boxes, but they also develop DC fast chargers that are used for highway charging stations such as those of Fastned in The Netherlands. ABB works together with municipalities and bus companies to make specialized, on-demand electric bus charging infrastructures for cities providing powers up to 600kW.

One of the most valued characteristics of ABB charging technologies is their ability to communicate with service centers for fast troubleshooting. Since this year, they also partnered up with the Formula-E races to promote and accelerate developments in electric mobility.

Today we talk to **Crijn Bouman**, a fast charging specialist at ABB.

What are the key technology enablers for compact, efficient and low cost fast chargers for electric vehicles ?

Of course, for compactness power electronics is the key. That is the main technical challenge there. But to make a good charger, actually, a lot of software is required and because it is a product which interacts with a vehicle, there is a lot of software communicating with the vehicle, with the battery management system of the vehicle. There is software for payment, user interfaces. So I would say it is a power-electronics product, with a very strong software component in there and actually the software is, I would say, for the customers we have is very key. Because, they make the payment applications, they make interaction with the user and all these items which are very visible to the outside world.

Charging stations often have different types of connectors. What has led to this and what do you foresee in the future?

The adoption of different connectors is actually due to industry politics, because the Japanese were first with electric vehicles and then the Americans and Europeans decided not to follow their standard. So, they created their own standard. And, also later the French also tried to bring in a new standard. It was in the end from a technical point of view: it is really makes no sense. But, it is just politics and standardisation committees in the end have found a way to say "agree to disagree". So, basically there is a standard with multiple n axes. So, charges now have three cables at the moment and soon it may go to two and maybe in ten or twenty years to one, but that's really a question mark.

How does charging technology for cars differs from that for buses or trucks?

Busses and trucks have much bigger batteries and typically the charging power is much higher. And, also the use case is very different. For example, a city-bus drives the same circle the whole day and it stops at the regular places. So, it needs actually a charging system which is very fast, but chargers the bus enough to drive one circle whereas if you are in a car you want to drive 300 km or so and maybe after 300 km you stop a bit longer. Maybe 15 or 20 minutes. So, I would say for the busses and trucks the charging power is much higher. It can go even to 500 kW and maybe later a MW or so. Where in car it is now in the range from 50 to 350 kW, which is also quite high-power, but the battery is just smaller.

What has motivated fast chargers to move from 50 kW charging power to 350 kW and up?

I think 50 kW was basically the initial standard for fast charging, which was based on the technology of that day, which is about 8-9 years ago where batteries were quite small and 50 kW was efficient to charge such a battery in about 20 minutes, but the range was very limited of these vehicles. And, what is happening now is that there are new electric vehicles coming to the market which can actually drive 4-5 hundred kilometres on a charge and in order to charge such a battery in 20 minutes you need up to 350 kW of battery power. So, basically the idea of the 350 kW new standard is that 15 minutes of charge will give you 400 km of range so it is very close to fuelling at the petrol station. 15 minutes and you can go 400 km then.

What is the role of smart charging and what are the biggest challenges for its implementation?

I think the role of smart charging will be quite big. It may not be as big in the fast charging domain as it is in the slow charging domain, because - let's say - the charging at home and the office is the biggest market for smart charging. Because, there you can shift energy over time. You can basically balance the grid with smart charging.

I think the biggest implementation issues are mainly that many stakeholders have to come together to build an application and there needs to be a business model behind it. I think the business model is really what - the implementation is not difficult, the business model is really the difficult case.

Why doesn't ABB offer bidirectional chargers with vehicle-to-grid capability? Is that going to change?

That may change in the future. At the moment we have actually a prototype of a vehicle-to-grid charger, but for smart charging the business model's hurdles are relatively small, so that business case is quite simple and straight forward to solve. For bidirectional charging there is also a very large regulatory aspect. It is that it is not allowed everywhere. And, the use case is that there are many stakeholders coming together, because if you use the battery to balance the grid, for example, it degrades the battery. Every use of a battery degrades it. So, you need to find a financial compensation for the loss of capacity of the battery versus the stakeholder, which is a different stakeholder, which is for example the grid owner. So the business model challenges are really not easy. And, therefore we think that vehicle-to-grid may have a good market, but it will take longer time. So it is something at the moment which is more in the experimentation stage and pilot project, but hopefully in the next five years will develop to a real product category. But we are still a bit monitoring how fast the real market will happen.

Tell us more about flash charging and opp-charging that ABB offers for electric buses.

Basically, we have multiple concepts. Because every use case has a different implementation. So, the flash charging is a very fast charging technique, which allows charging in one minute for city-bus applications, so charging at the bus stop. Then you have a technique that called opp-charge that is actually a more mainstream technique which is more based on the idea of charging at the end points in the routes, so that charging time is about 5 minutes more or less. And for electric cars the use case is mainly, I would say, on the highway maybe 15 to 20 minutes, but there is also other use cases like supermarkets where half an hour to 45 minutes would be a good use case. Or if you would go for example to a concert or a commercial shopping mall, where you spend maybe two hours then that is an appropriate use case. So, in the end is our philosophy is mainly that the use case really defines the charging time because the consumers have a certain behaviour. They will not change this so you have to adapt the charging time to the location where people spend certain amount of time.

Do you see both slow AC charging and fast DC charging co-existing in the future?

Absolutely, I think the majority of charging at home and in the office will be AC charging for now. And, the faster you go the more sense it makes to have DC charging. I would say that there is also a possibility that in the future DC charging at home can come. The combination of solar and battery storage et cetera, but the timeline is maybe a bit longer. They absolutely will go exist at least for the next ten years, for sure.

What are the unique selling points of ABB EV chargers?

I would say we have a quite broad portfolio for all the use cases and our chargers are very well. We have invested a lot into the software site of the charger. So, the applications, building, payment, connectivity, remote diagnostics, because to make a charging operation commercially attractive your running costs need to be very low. And, remote diagnostics, remote service capability are absolutely crucial to many costumers. So, we invested a lot in that. And, we invested a lot into the integration with payment applications, integration with apps, with smartphones et cetera, which defines actually the user experience. So, there compared to others we have a really strong position In the Asian region we are maybe not the market leader but also a strong player. And, I think compared to the others we have more focus on the application for the end-user. So, how does our customer actually use the product? It is not just a box with hardware, it has software, it has a user interface, it has connectivity, payment application and that is very crucial to our customer base.

What is the future of EV charging? And do we even need to charge our cars if they have their own solar panels?

That is an interesting question. Actually, I mean in general the future for electric cars is very bright because every car will be electric. It is just the question if it is one or two decades. And, three decades for sure not. It is one or two decades. So, there is really a bright future. I think there will be a very wide variety of charging options. If it would be feasible to have solar panel on the car. Maybe technically at some point it is feasible, but the question if it is practical for all the use cases. Not all cars are always in the sunlight and we are living in the sunny country of the Netherlands where maybe there is sometimes a cloud. So, I have my doubt if that is a solution for all. But maybe there is a possibility to have that technology working in certain regions. So, I think it is interesting. In general, the outlook for EVs and EV charging is very bright I think.

Is the battery technology even prepared for 350 kW charging?

Well, of course the first generation of electric vehicles where not capable to do that but there is now a next generation coming, which is actually is capable of charging at that rate. Also, the battery capacity will be very big. Much more than 100 kW hours, so it means that the relative charging speed compared to the battery capacity, the C-rate, is actually in the 2-3 C-range. And what we are seeing is that battery manufacturers are now just starting to design their products according to this specification, so they have the requirement from the automotive industry that any battery needs to be charged within 15 to 20 minutes, so that means a 3C charging rate and they are just adapting their chemistry and the way the battery is build. They are adapting it to the requirements of the automotive industry. So, I would say the previous generation cars was not capable but I think in the next generation cars many of the vehicles will be capable to charge in the range of 200 to 350 kW magnitude.

Summary

We have come to the end of this module on EV charging technology. In the first lecture, we saw various charging methods for EVs. The three common ways are conductive charging, inductive charging and battery swap. Conductive charging is the most common charging method right now and it has two categories: AC and DC charging. The second method is inductive charging and consists of two types: static and dynamic charging. The final method is battery swap. These charging methods have their own advantages and disadvantages. While battery swap provides the quickest "charging" time, it faces a big challenge in requiring standardisation across EV manufacturers for the battery and car design. Inductive charging provides maximum convenience to the user but has a higher cost and relatively lower efficiency than conductive charging.

The second lecture was on AC charging of electric vehicles. In its simplest form, AC charging uses an onboard charger to convert AC power from the conventional AC grid to direct current or DC power to charge the traction battery. Then we saw the essential components needed in an AC charging station for a safe and reliable charging process. There are four main types of AC charging connectors: Type 1, Type 2, Type 3 and proprietary connector used by Tesla. The proximity and control pilot of Type 1 and Type 2 chargers provide the control of the charging process. Finally, we understood how a simple formula could be used to estimate the charging power and charging time for AC charging.

The third lecture was on DC charging of electric vehicles. We looked at the power flow for DC charging from the DC charger to the EV battery. There are five types of DC charging connectors used globally: CCS-combo 1, CCS-combo 2, Chademo, Tesla DC connectors and the Chinese GB/T connector. Even though DC charging is quite attractive in the sense of high power charging with short charging times, fast charging limited due to the maximum power that the charging cable and EV battery can handle and its impact on the battery lifetime.

The fourth part was on smart charging of electric vehicles, vehicle-to-grid technology and the necessary ICT protocols. Smart charging is a series of intelligent functionalities to control the EV charging power in order to create a flexible, sustainable, low cost and efficient charging environment. There are several benefits of smart charging and it has huge potential: EV charging can be controlled based on renewable generation, energy prices, grid loading and how the EV can be used as a storage and as an emergency power supply. Vehicle-to-grid is a special case of smart charging where the energy from the EV battery can be used to feed power to homes, buildings and to the grid.

The next lecture looked at charging electric cars as an evolving ecosystem with many different machines and stakeholders that must be able to exchange information using various protocols. Open protocols will be crucial for the development of the charging infrastructure market. Finally, we learnt about current and future trends in EV charging technology through the case study of ABB charging infrastructure.

Practice problems

Question 1

Vehicle to grid option requires a battery charger with:

- o Unidirectional power flow to discharge the battery
- o Unidirectional power flow to charge the battery

- o Bidirectional power flow for charging and inverter modes alike
- o Different batteries

Question 2

There are two EVs with 85 kWh and 24kWh battery packs with a NEDC range of 500 km and 200 km, respectively.

a. What is the average energy consumption per km of EV 1 and EV 2, respectively?
   - o 170 kWh/km, 120 kWh/km
   - o 170 Wh/km, 120 Wh/km
   - o 5.8 Wh/km, 8.3 Wh/km
   - o 5.8 kWh/km, 8.3 kWh/km

b. Calculate charging power needed for fast charging the battery of EV1 to a fully charged state from an empty state in 5min, 30 min, 60 min time, respectively?
   - o 1.02 MWh, 170 kWh, 85 kWh
   - o 1.02 MW, 170 kW, 85 kW
   - o 1020 kW, 17 kW, 85kW
   - o 85 kW, 85 kW, 85 kW

c. If the two EVs were to start with a full battery and drive 830 km from Amsterdam to Munich, how many fast charging stops would they need enroute to complete the trip, respectively ? Assume that they fast charge when the battery is empty, charge up to 80% SOC at every stop and can always find a charger enroute when needed.
   - o 1 stop, 3 stop
   - o 2 stop, 2 stop
   - o 2 stop, 3 stop
   - o 1 stop, 4 stop

Question 3

The owner of a Renault Zoe EV that supports 43kW fast AC charging drives to a Tesla DC supercharger in Europe and notices that the plug looks like the one on his EV.

a. Is his observation correct?
   - o Yes
   - o No

b. If so, should he plug in and charge?
   - o Yes
   - o No

Question 4

Which of the following are challenges in commercializing battery swap technology that need to be overcome?

- o The requirement of standardized battery interfaces across multiple car manufacturers
- o Consumer acceptance of not owning a battery
- o Accurate state of health estimation is required for batteries coming different electric cars
- o All of the above

Question 5

State if the below statements are **true** or **false**.

a. An EV parked for 5h and requiring 50 kWh energy from a 10kW charger, offers no flexibility in controlling the charging power for smart charging. _______

b. One of the challenge in DC charging service is the adverse impact on the power system when high current demand from charging superimpose with the peak demand hours. _______

c. The battery swap approach has the challenge of getting market acceptance. The main reasons are: The requirement of having standardized battery interface across multiple car manufacturers. Second is the consumer acceptance of not owning a battery. Third is that in order to monetize the battery usage, there should be a fool-proof way to estimate the batteries state of health. _______

Resources

[1] CEN/CENELEC/ETSI Smart Grid Coordination Group, "Final report of the CEN/CENELEC/ETSI Joint Working Group on Standards for Smart Grids," *Etsi*, 2011.

[2] Eurelectric, "Smart charging : steering the charge , driving the change," *Eurelectric*, 2015.

Final model quiz

Section 2.1

Question 1

Match the following terms with its description.

• The advantage of this charging method is that the battery can be recharged anywhere there is a standard electrical outlet.	• Static inductive charging
• This charging method can provide fast charging >50kW and is not limited in its weight and size.	• Dynamic inductive charging
• There are minimal safety hazards in this charging method and therefore, is suitable in all-weather conditions.	• DC conductive charging

• In this charging method, there is lower Depth Of Discharge (DOD), which leads to a longer battery lifetime, because the car can be charged continuously while driving.	• AC conductive charging
• There is no range anxiety in this charging method and it is quick and easy like refilling your gasoline tank.	• Battery swap

Question 2

State if the below statements are true or false.

a. There is no size and weight restrictions when having an off-board charger and therefore, this set up provides more flexibility in terms of the power that can be delivered.
   - True correct
   - False

b. Charging times with battery swap technology will be similar to that of refilling the fuel tank of a combustion engine vehicle.
   - True correct
   - False

Question 3

The dynamic inductive charging is still in the experimental stage because there are many challenges to standardize it. Choose the option that describe a possible challenge.

- Real-time coil misalignment is hard to estimate for different types of cars and driving conditions. correct
- Presence of foreign objects on the road will affect power transfer efficiency in a positive way.
- Battery size is small as the battery can be charged regularly on the road.

Section 3.2

Question 1

An EV is charged using a Type 2 connector with 230V single phase AC and 400V three-phase AC.

Single phase: $P_{ch}=V_{ac}I_{ac}$

Three phase: $P_{ch}=\sqrt{3}(V_{3ac}I_{ac})=3V_{ac}I_{ac}$,

where V_{ac} is the single-phase AC voltage (V), V_{3ac} is the three-phase line-to-line AC voltage (V) and $V_{3ac}=\sqrt{3}V_{ac}$, P_{ch} is the charging power (W or kW) and I_{ac} is the grid current (A).

a. What is the AC current for single phase AC charging when charging at a power of 7.36 kW?
   - 16 A
   - 32 A

- o 10 A
- o 25 A

b. What is the AC current for three-phase AC charging when charging at a power of 7.36kW?
   - o 15 A
   - o 10.6 A
   - o 18.4 A
   - o 6.1 A

Question 2

A Tesla owner driving 100 km every day in Europe wants to charge his EV in 2 hours in the evening using his AC power connection at home. The car consumes 170Wh/km.

a. Which charger plug must he install at his home?
   - o Type 1
   - o Type 2
   - o CHAdeMO
   - o GB/T

b. What must be the minimum AC current rating for single phase and three phase AC charging that he must install at his house, respectively?
   - o 230V 32A, 400V 32A
   - o 230V 63A, 400V 16A
   - o 230V 63A, 400V 32A
   - o 110V 63A, 400V 32A

c. What is the safe charging mode that he must implement (recall Section 2.3)?
   - o Mode 1
   - o Mode 4
   - o Mode 3
   - o Mode 5

d. What must be the minimum AC current rating for single phase and three phase AC charging that he must install at his house if he decides to charge overnight in 8 hours?
   - o 230V 10A, 400V 16A
   - o 230V 63A, 400V 16A
   - o 230V 32A, 400V 16A
   - o 230V 10A, 400V 5A

Section 3.5

Question 1

CAN bus communication is used between the DC charger and EV in

- o CHAdeMO only
- o Chinese GB/T connector only
- o CCS/COMBO only
- o In Chademo and Chinese GB/T

Question 2

In this exercise we will try to learn about the effect of battery ampere hour capacity on the C-rate for a given charging power. While fast charging leads to battery degradation due to higher C-rates, this phenomenon depends on the battery capacity. For the same charging power, higher the ampere hour of the battery, lower is the C-rate and lower is the corresponding battery degradation.

a. There are two batteries of 100 kWh and 25 kWh with a nominal voltage of 400V. What is the nominal ampere hour capacity of the two batteries, respectively?

- o 100Ah, 25 Ah
- o 250Ah, 62.5 Ah
- o 400Ah, 100Ah
- o 40 MWh, 10 MWh

b. If both the batteries are charged at a power of 100kW, what are the respective C-rates of the two batteries?

- o 4C, 1C
- o 0.4C, 0.1C
- o 1C, 4C
- o 40C, 10C

Question 3

Indicate whether the following statements are **true** or **false**.

a. Currently, the IEC 61851-1 protocol is used for communication between the EV and charging station (EVSE). For the future, the ISO/IEC 15118 protocol is being developed for communication between the EV and EVSE to achieve advanced charging functionalities. ________

b. Electric vehicles with longer parking time and lower energy demand can offer more opportunity for smart charging than vehicles with shorter parking times and higher energy demand. ________

Question 4

Here below you see a paragraph explaining the working of charging method. Choose between **AC charging** and **DC charging** to correctly fill in the blanks of the below paragraph.

___________(1) needs higher investment for installation of the charger compared to ___________ (2) for the same charging power. Typically, ___________ (3) offers lower charging powers than ___________ (4) and hence needs relatively longer charging times.

5 Future electric mobility

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5.1 Future trends in electric cars

In this section we will briefly look at the important technologies and emerging trends in electric vehicles and charging infrastructure design. We will look at the powertrain design, solar electric vehicles and fuel cell electric vehicles, future charging technologies, and finally at autonomous electric vehicles.

First, let us look at the key trends in electric vehicle powertrain and battery technology. Amongst EV manufacturers, it has now become unofficially recognized that EVs in the future must have a battery capacity that can provide 200-300 mile range. This is more than sufficient for city commutes and removes the range highway for long distance driving in combination with highway fast-charging.

Secondly, manufacturers are moving towards designing electric vehicles from the bottom up rather than building them based on existing combustion engine cars. This approach provides more flexibility in design, scope to add larger batteries and is expected to reduce the cost of the vehicle in the long run.

A third trend is to integrate the different powertrain components and controllers in the vehicle. This allows an increase in the power density with a subsequent reduction in vehicle weight, reduces the wiring requirements within the car and provides more efficient ways for thermal management of powertrain components. The use of wide bandgap semiconductor devices such as silicon carbide and gallium nitride would help increase the switching frequency of power converters and hence increase power density.

On the battery side, a vital parameter to realize more efficient EVs in the future is energy density. Table 5.1 shows the estimated maximum energy density limits of different battery chemistries. It can be seen that there is theoretically up to a five-fold potential to go from the current Lithium-ion energy density of 200Wh/kg to up to 1000Wh/Kg possible with lithium-air batteries. There is hence a huge potential for research into the materials, stability, safety, cycle life, power and energy density and manufacturability of these emerging battery technologies.

Table 5.1 Battery maximum estimated energy densities

Chemistry	Max. Energy Density (Wh/kg)
Li-air	900-1000
Li-sulphur	400-500
Mg-ion	350-400
Li-ion (future)	250-300
Li-ion (now)	200-250

Besides this, supercapacitors can provide high power densities when used in collaboration

Figure 5.1 Nuna 8 Solar race car (on the left) and Stella Solar family car (on the right)

with a battery for peak powers requirements during acceleration and braking.

The second technology for future electric vehicles are solar electric vehicles. In Figure 4.1, you can see the solar powered electric vehicles Nuna and Stella designed by student teams at the Delft University of Technology and Eindhoven University of Technology from the Netherlands. While the Nuna is a designed to be a race car, the Stella is a family car. The common feature in both vehicles is that solar panels are used for charging the on-board battery and provides practically all the energy needed for driving. For example, in the Nuna 8 solar race car, 391 Monocrystalline silicon solar cells with an efficiency of 22.5% were used. Other PV technologies can be used as well depending on the flexibility of the cells, efficiency, the colour of the cells and of course, the cost.

In Figure 5.2, we can see the typical drivetrain components of a conventional electric car showing the battery, DC-DC converter, and DC-AC motor drive. In case of a solar electric vehicle, solar panels are included in the drive train through a maximum power point tracking or MPPT, DC to DC power converter. This converter ensures that solar array is operated at it optimal power point and the voltage of the PV array is matched with that of the high voltage bus inside the EV. While providing all the power requirements of a commercial electric car using on-board solar cells would not be possible in the near future, several EV manufacturers

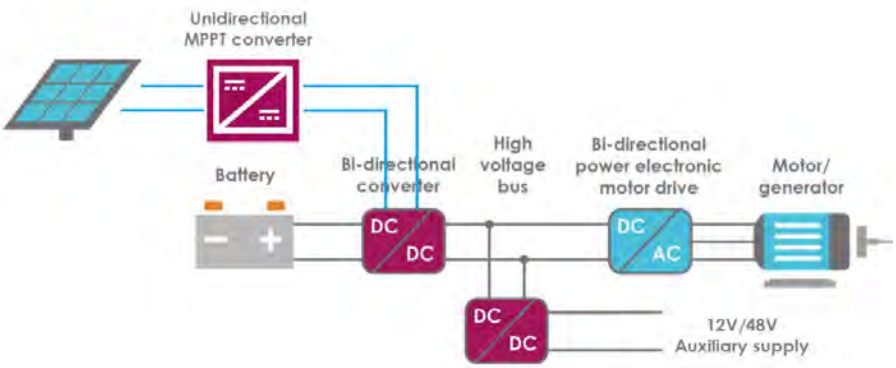

Figure 5.2 Solar EV: power flow schematic

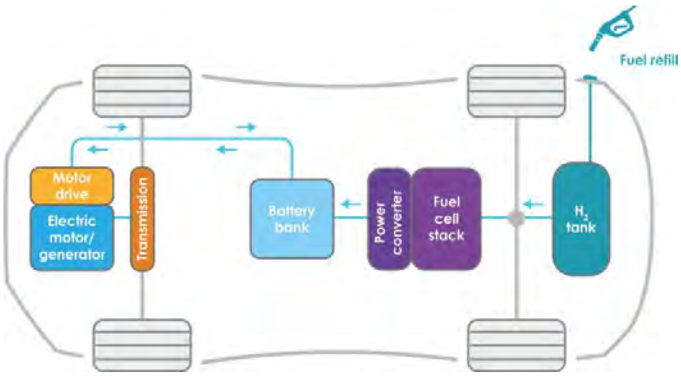

Figure 5.3 Fuel cell electric vehicle schematic

have announced to have solar cells integrated into the car roof. This will partially provide the driving energy, thereby extending the car range.

While solar cells can help in increasing the range of an EV, fuel cells powered by hydrogen can provide long driving range and quick fuelling times similar to a combustion engine vehicle. A fuel cell electric vehicle is essentially an electric vehicle with a battery with the key feature of using a fuel cell to charge the battery and power the drivetrain. Production versions of Fuel cell vehicles have been offered by several leading car manufacturers including Toyota, Honda, Hyundai, and Mercedes. While high costs of the vehicle and charging infrastructure have limited its growth till now, fuel cell EVs are expected to emerge back in the future and play a key role especially for long distance heavy vehicle transport such as trucks.

Next, let us look at vital technologies for future of EV charging namely, battery swap technology, wireless charging, smart charging, and V2G. Battery swap works on the basis of switching out the depleted battery of an EV and replacing the same with a full battery. Battery swap has plenty of advantages amongst which the most important are the fast times to replenish an empty battery and the flexibility to charge the battery at the swap station over a longer time when compared to fast charging. However, the main challenge for battery swap comes from the vehicle design. Large-scale adoption of battery swap technology requires EVs to be designed with a standardized battery, battery interface and vehicle chassis that allows easy removal, charging and placement of the batteries back to the vehicle. If the traveling routes, load factor, and vehicle fleets can be known, which is quite often the case for public transport or commercial logistics; battery swap can provide a low cost, flexible and convenient method for EV charging in the future. A demo site from Hyundai is shown in Figure 5.4.

Figure 5.4 Battery swap demo station

Speaking of convenient charging, wireless inductive charging of electric vehicles would provide ease and convenience of charging without the requirement of any charging cables. The technology uses two electromagnetically linked coils that exchange power at high frequency. As shown in the drawing in Figure 5.5, the primary coil is placed on the road surface and linked to the electricity network while the secondary coil is placed on the vehicle and charges the battery. Wireless charging systems are now commercially available for various electric vehicles. In the future, it could come as a default charging system for electric cars based on the SAE J2954 standard. The extension of wireless charging would be on-road charging where inductive charge pads are placed along the roads so that electric cars can wirelessly charge while driving. It's a technology that can dramatically reduce the cost of electric cars as they would need a smaller battery and move this cost to the charging infrastructure.

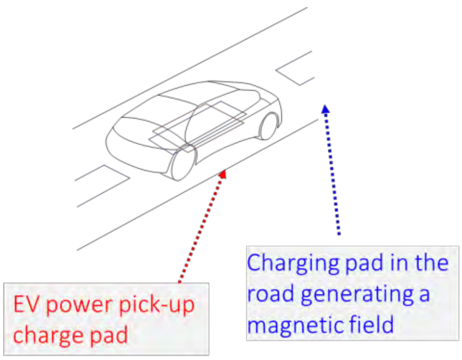

Figure 5.5 Wireless charging on the road: a representation

An excellent example is the Online Electric Vehicle system, developed by the Korea Advanced Institute of Science and Technology (KAIST) where 100kW wireless charging power is provided to buses at an air gap of up to 17cm at 75-85% efficiency. This has resulted in the battery size reducing to 20%.

There are some other future developments to mention, in which different technologies are integrated. Solar and wind energy next to the road can, for example, power the electric vehicles by on-road charging. The roads can be self-healing, without potholes and cracks. The coils used for inductive charging could make the same road with special asphalt, also self-healing. The roads can generate energy adopting solar roads technology, where solar cells are integrated in the road itself.

The third key charging technology is smart charging, especially from renewable sources of energy like wind and solar and vehicle to grid technology. Smart charging of EVs whether it is AC, DC or wireless involves the control of the charging power as a function of time. By controlling the charging power, several benefits can be achieved in the future, namely:

- Reducing the charging cost;
- Charging based on renewable energy generation;
- Using the car as a storage for the renewables and a grid back up with the use of vehicle-to-grid;
- Providing demand-side management and reducing the peak load and losses in the distribution network;
- Providing ancillary services in the form of voltage and frequency control to the grid.

Charging protocols like the ISO 15118, OCPP, OSCP, OCHP and OCPI will be important for communication between the various entities in the smart charging chain like the EV, charger point operation, e-mobility service provider and the transmission and distribution system operator.

The city of Amsterdam has been making a demonstration of the vehicle to grid concept. In this project, running from 2014-2017, 2 well working Vehicle 2 Home installations were installed in the city. Partners cooperating in this project were Engie, Alliander, Mitsubishi Motors, Amsterdam Smart City and Amsterdam University of Applied Sciences. RVO provided

Figure 5.6 Tesla automated electric vehicles project

Table 5.2 Automated electric vehicles levels

Level	Functionality
0	No autonomous capability
1	In certain conditions, the car controls either the steering or speed.
2	In certain conditions, the car can steer, accelerate, and brake.
3	In many conditions, the car can manage most aspects of driving.
4	In many conditions, the car can autonomously drive itself
5	In all conditions, the car can autonomously drive itself

a subsidy via TKI Switch 2 Smart Grids. This video made by Amsterdam smart city on V2G gives an overview of the pilot done in Amsterdam, the lessons learn and the challenges faced. The video is in Dutch with English subtitles.

Lastly, the technology that can totally change the mobility landscape is **autonomous driving**. Self-driving with limited capabilities have already been built into existing electric cars such as those from Tesla. An example of Tesla's project is given in Figure 5.6. Self-driving vehicles open up a plethora of opportunities in the future such as shared and connected mobility, cities decongested of cars and parking spaces, higher utilization of vehicles, lower cost of mobility and more efficient point-to-point connectivity. A combination of different kinds of sensors such as a video camera, Light detection and ranging or LIDAR, Radar sensors, Ultrasonic sensors, and GPS are used by the vehicles to understand the environment, and a computer on board controls the movement of the car. Autonomous driving is expected to be developed over 5 levels starting at Level 1 where the car can control either the steering or speed under certain conditions to Level 5 where the car can autonomously drive itself under all conditions. Table 5.2 summarizes the automation levels for electric vehicles.

To wrap up this lecture, we looked at the key emerging technologies for future electric vehicles focussing on the vehicle powertrain and battery and solar and fuel cell electric vehicles. Battery swap technology, wireless charging, smart charging, and V2G will be four key technologies for charging of cars in the future. Finally, self-driving cars can change mobility as we know it and change the landscape to shared and connected cars in the future.

Practice problems

Question 1

EVs require 200-300 mile battery range and typical energy consumption of a 4 person car varies in the range of 100-200Wh per km. What would be the required size of the battery considering this variation, if the drivetrain has a typical efficiency of 85%?

- o 32 to 96 kWh
- o 37 to 114 kWh
- o 23 to 71 kWh
- o 200 to 300 kWh

Question 2

The benefit of designing an electric car bottom-up from scratch as against designing it from an existing gasoline car (More than one right answer is possible):

- ☐ Scope to add larger batteries

- ☐ Ability to use permanent magnet motors
- ☐ Battery technologies with a lower price can be used
- ☐ More flexibility in the location of components

Question 3

The use of a higher energy density battery technology in an EV facilitates a

- o Lighter car for the same the same weight of the battery
- o Higher battery power for the same kWh of the battery, C-rate
- o Longer range for the same weight of the battery
- o Lower battery power for the same kWh of the battery, C-rate

5.2 Wireless charging of EVs

Recently, wireless charging of mobile phones has become a possibility, and one does not need to connect a charging cable to phone to charge it. This technology can be extended for charging electric car batteries as well. During wireless power transfer, power is transferred from a source to a load without the need for a conducting cable in between. Different types of wireless power transfer techniques are possible based on energy carrier medium. They can be mainly classified as inductive, capacitive, microwave, laser, and acoustic power transfer.

An inductively coupled contactless power transfer (IPT) system is capable of efficiently delivering power from a stationary primary source to a movable or stationary secondary source over a relatively large air gap. Although the conductive charger has a lot of advantages such as simplicity and high efficiency, the inductive charger is easy to use and is suitable for all-weather conditions. This is because there is no direct electrical contact between the vehicle and the charger preventing the possibility of a shock or an electrical arc. In case of stationary/static charging, parking lots can be upgraded to charge EVs with the comfort of not plugging in any charging cables. Such systems can be buried or flush-mount, thereby not affecting the façade of a city and being safe from vandalism and unfavourable weather conditions. The main drawbacks of this charger are the high investment cost and the relatively higher losses when compared to conductive charging.

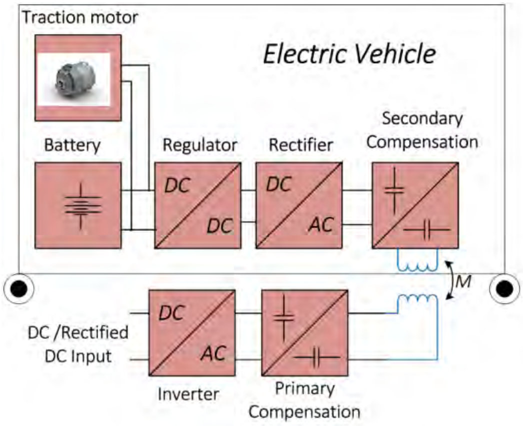

Figure 5.7 Inductive Power Transfer (IPT) components

A possible solution for an inductive charger is shown in Figure 5.7. The principle is based on the magnetic coupling between two windings of a high frequency air core transformer. One of the windings is installed in the charger terminal while the other is embedded in the EV. Firstly, the main AC supply of frequency 50-60Hz is rectified and converted to a high-frequency AC power of <100 kHz within the charger station. This high-frequency AC current is then inductively transmitted to the receiver/secondary coil. Finally, this high frequency induced current in the secondary is converted to DC via a power electronic rectifier, which is suitable for charging the battery pack. Due to large airgaps, the leakage inductance of the air core transformer is comparable to its mutual inductance. This leads to low coupling coefficient (k<0.4) compared to k = 0.95-0.99 in conventional iron core transformers. Capacitors are placed in the circuit in either series or parallel configuration to negate the effect of this large leakage inductance. This results in resonant operation and thus leads to high efficiency of power transfer (>85%).

A very important aspect of inductive charging systems is the health risk associated with the exposure of individuals at radiation. The leakage fields that permeate the space around the charge-pad can impact both the health of a living entity in close proximity. It can also result in unwanted heating of foreign objects that are close by. Different regulating bodies have published standards for limiting exposure – ICNIRP (International Commission on Non-Ionizing Radiation Protection), IEEE etc. There are different Z classes where Z is the air gap (distance) between the primary and secondary coils: Z1 (100-150 mm), Z2 (140-210 mm) and Z3 (170-250 mm) and different power classes - 3.7, 7.7, 11, 22 kW as per upcoming standard SAE J2954.

Various systems have been developed over the last decade aimed for both charging of both personal and public transport vehicles. These prototypes range from 2 kW to 200 kW of power delivered at frequencies around 40-100 kHz with overall efficiency from AC mains to DC battery ranging from 80 to 95% . Charging distances are 50 mm-400 mm for production cars and public transport vehicles. Guiding the magnetic fields in order to reduce the losses is required for these systems to be viable, as they have to be mounted close to the ferrous vehicle body. A third trend is to integrate the different powertrain components and controllers in the vehicle.

Practical examples of stationary inductive charging include bus based wireless electric vehicle charging systems (WEVC). Such systems have helped in reducing the weight of on-board batteries and have improved efficiency. For example: Conductix-Wamplfler's WEVC in buses in Torino, Geneo and s'Hertogenbosch in the Netherlands. Efficiencies of more than 90% are reported at 60, 120 or 180 kW. WAVE IPT, a spin-off from Utah State University is working on 50 kW IPT systems achieving more than 90 % efficiency. They are expecting to install IPT systems with 250 kW charging. OLEV, a spin-off from Korean Advanced Institute of Science and Technology (KAIST) developed a third generation of wireless power transfer in with a power transfer efficiency of 83% at a 20-cm air gap.

Companies like Witricity, Qualcomm Halo, Conductix-Wampfler, Bombardier, Momentum Dynamics, HEVO Power etc. are building market ready charge-pads for electric vehicles charging using IPT systems. Witricity that started out of Massachusetts Institute of Technology, have developed systems that deliver 91–93% efficiency at 11 kW power transfer. HaloIPT that started out as a spin-off from the University of Auckland, works extensively in a patented "Double D" magnetic structure for power transfer. Qualcomm acquired Halo in 2011 and they are involved in developing systems from 3.3 kW to 20 kW with > 90% efficiency.

Dynamic charging is the concept of charging the battery of EV or even using it for traction when the vehicle is in motion. This is usually achieved by having sectional IPT systems/ repeated charge-pads on the road. An example of dynamic charging IPT systems on the road was demonstrated at Oak Ridge National Laboratory (ORNL). Dynamic charging can enhance battery life by charging with small packets of energy while nullifying range anxiety in long trips caused due to limited battery size. For example, for an EV with a battery of 24 kWh, 500 km range can be achieved by IPT system of 25 kW with 40% road coverage [1]. In a related study in California, the combination of dynamic and static charging is shown as cost effective compared to gasoline vehicles fuelled at $2.50 and $4 per gallon [2], [3].

Operation principle

Let us understand the operation principle of an IPT system where coils exchange power over air (air core configuration). The air gap in a IPT transformer configuration is typically large in order of tens of mm. So, they have a large leakage inductance (L_1-M, L_2-M) and low mutual coupling (k) which implies a large magnetizing current.

Figure 5.8 shows the circuit representation of a inductive charging air core transformer. L_1 and L_2 represent the self-inductance of primary and secondary winding respectively. M is the mutual inductance between the transformer winding and k is coupling coefficient ($0 \leq k \leq 1$) such that:

$$M = k\sqrt{L_1 L_2} \tag{5.1}$$

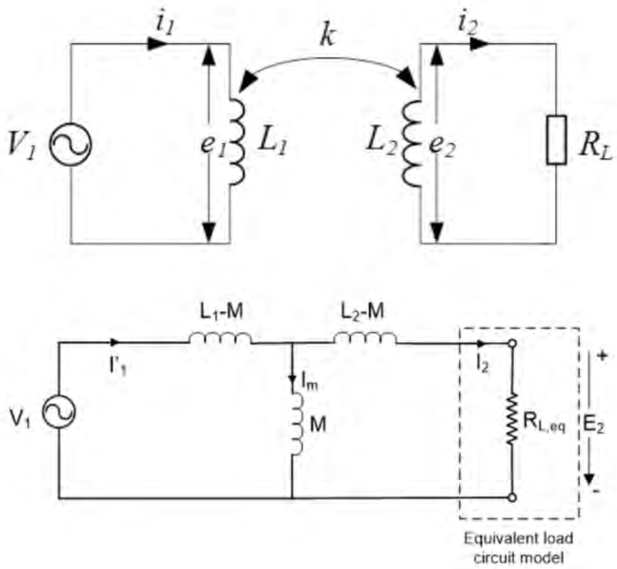

Figure 5.8 Air coupled inductive power transfer circuit (top) and its equivalent circuit (bottom)

For IPT system with air as a power transfer medium, k is small and so is M. This results in a large leakage inductance which reduces the power transfer efficiency. The leakage inductances L_{L1} and L_{L2} on the primary and secondary side can be described as:

$$L_{L1}=L_1-M \tag{5.2}$$

$$L_{L2}=L_2-M \tag{5.3}$$

Ideally, one wants a large value of mutual inductance and a low value of leakage inductance. In the case of a ferrite core transformer, the coupling ratio is very high, i.e. $k \approx 1$ and therefore $M>>L_{L1}$. But in IPT systems, since k is low, this however does not occur. Consequently, a large amount of reactive power is drawn from the source to provide the reactive power of the leakage inductance. Hence, very little power is transmitted to the load resistance R_L if the coupling coefficient is low, say below 0.4.

Compensation

For the air coupled inductors, the low coupling (k<<1) and the high leakage inductances prevent the system from delivering power to the load at high efficiency. However, it can be

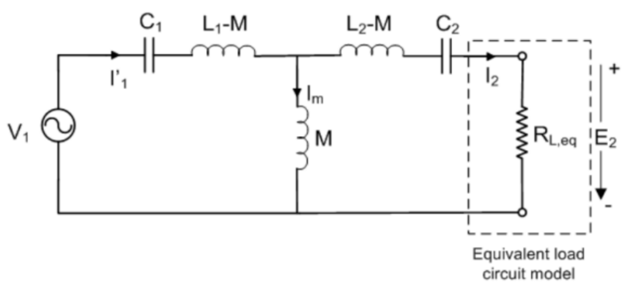

Figure 5.9 Basic compensated coupled inductor power transfer circuit

compensated for that. The impedance of an inductor is in the positive *j* direction while that of an capacitor is in the negative *j* direction. Compensation capacitors are used in IPT applications to increase the efficiency and the capability of the system they are used in. Capacitive compensation is used in both the primary and secondary windings of the IPT transformer. These capacitors essentially store and supply reactive power to and from the secondary and primary windings, reducing the amount of reactive power drawn from the supply. By connecting two capacitors into the circuit as shown in Figure 5.9 referred to as series-series compensation, one can remove the effect of the high leakage inductances if it can be ensured that:

$$\omega = 2\pi f \tag{5.4}$$

$$\omega^2 = 1/L_1C_1 \tag{5.5}$$

$$\omega^2 = 1/L_2C_2 \tag{5.5}$$

This is in fact creating a resonance between the *L*-*C* components on the primary and secondary side. By doing so, the current drawn from the source is purely used to provide the load power and the reactive power needed by the leakage inductances are provided by the compensation capacitors. The capacitive compensation thus helps improve the overall power transfer capability and efficiency of the system even when the coupling coefficient is low.

Other modes of wireless power transfer include those that use Microwaves in the frequency range of 300 MHz-3 GHz used, for example, in Space Power Satellites. Finally, there is laser power transfer using electromagnetic radiation at a very high frequency and acoustic power transfer at frequencies in the range of 20 to 100 KHz. Inductive power is the most popular method of wireless power transfer used for charging electric vehicles batteries and will be the focus of this section.

IPT systems have several advantages and disadvantages compared to conductive charging, all of which summarized in Table 5.3. The three advantages of such systems are that we do not need to add charge poles to the streets and hence are aesthetically more compatible especially for traditional cities. Also, the wireless charge-pads in the ground can be flush-mounted/ buried. Further, they are safe and convenient as the EV can be charged at the comfort of parking without plugging any cable into the system and possibilities for tripping on the cable are avoided. Wireless charging system for EVs are already commercially available today and this is only expected to increase in the future. The main disadvantages of the IPT systems are the higher losses in the system. The cost of the system is relatively higher as well

Table 5.3 Static inductive charging advantages and disadvantages

Advantages	Disadvantages
Aesthetically favorable, no vandalism	5-10% higher losses
Safety	Higher costs compared to AC, DC charging
Comfort	Extra converters compared to AC charging

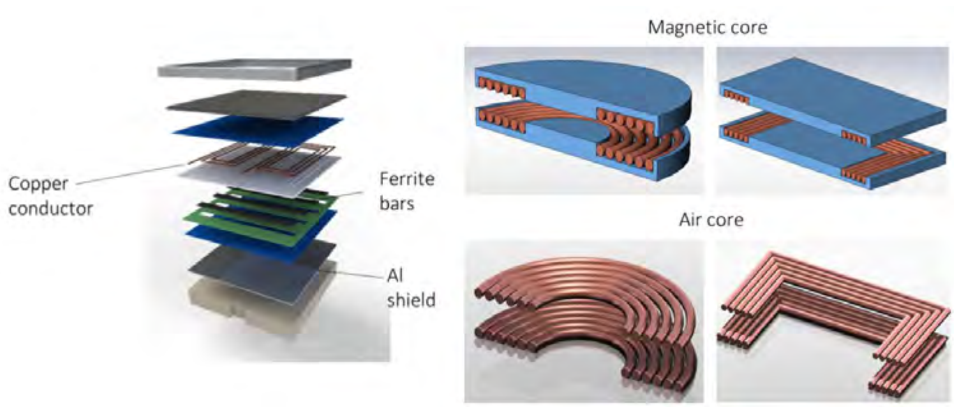

Figure 5.10 Materials and configurations of charge-pads

due to the additional converters and two charging pads that are needed, one on the ground and one on the vehicle. However, the power efficiency of these systems are improving and will become competitive with respect to conductive charging.

Let us now look at the key parts of an IPT system and understand how it works. In the first step, the IPT system takes power from the 50Hz AC-mains which can be single phase or 3 phase and is rectified to DC using a dc-to-dc converter. Alternately, power directly from a DC source can be used as well. This DC input is then converted to high-frequency AC power using a DC-AC inverter. SAE J2954 standard for EV charging earmarks a small band between 80 – 90 kHz for wireless charging of EVs with a center frequency of 85 kHz. The inverter produces this 85kHz pulse width modulated or PWM voltage which is fed to a wireless charging pad. A charging pad consists of conducting coils spread over a surface in a specific shape and may or may not have magnetic material. One charging pad is placed on the ground and is called the primary or base-pad and second pad is placed underneath the vehicle and is called the secondary or vehicle-pad. At close proximity, the primary and secondary coil are electromagnetically coupled to each making it possible to exchange power between them. The inverter PWM voltage creates a high-frequency sinusoidal AC current and voltage in the base-pad by means of resonance with a compensation circuit consisting of capacitors. The sinusoidal AC power from the primary coil is transferred to the secondary coil due to the electromagnetic coupling. The compensation circuit helps in reducing the reactive power that needs to be delivered by the source, thereby increasing the efficiency of the system. On the vehicle side, AC power from the secondary coil is then rectified using an AC-to-DC rectifier and regulated using a DC-to-DC converter to charge the EV battery.

As we show in Figure 5.10, a well-designed charge-pad has three important components. First is current conducting materials. Typically, copper wires with low resistivity and designed for high-frequency operation are preferred. Litz wire is a special kind of copper wire that is widely used in designing charge pads that is a spool of stranded and twisted thin wire with each strand insulated from each other. Foil conductors that are composed of thin foils bunched together can also be used to reduce high-frequency losses in the charge pad. Secondly, Magnetic flux channeling materials are required. Examples of these are ferrites which have a high relative magnetic permeability, around 16-640 and is hence a good conductor of magnetic fields. Finally, Magnetic flux shielding materials. An example of this is an Aluminium layer below the ferrite bar. The used of the shielding material is that it prevents the magnetic flux from penetrating below the ground, thereby only permitting uni-directional flux movement from the ground pad to the vehicle pad.

In reality, the two charge pads can be of several shapes and can have different sizes of coils namely, circular or rectangular. In a few cases, each pad can be composed of magnetic materials such as ferrites as shown in the blue parts on the right of Figure 5.10.

An interesting application of wireless charging is the ability to the charge the electric car while it is driving. This is referred to as dynamic charging or on-road charging of EVs. A rendering of this technology is shown in Figures 5.11 and 5.12. Here a single large base-pad or multiple smaller base pads can be placed underneath the road with or without magnetic material like ferrites. Power electronic converters connected to these charging pads help generate magnetic fields which are then picked up by the charging pad placed underneath the vehicle. Hence, the vehicle picks up power wirelessly as it drives and this is used to both supply the energy for driving as well as to charge the battery. A useful consequence of this is that electric vehicles need smaller batteries. Further, the ability to charge while driving removes range anxiety and provides convenience for the user. On the flip side, on road charging has the disadvantage of a relatively higher cost. The efficiency of the system is reduced when there is misalignment between the base charging pad in the road and the vehicle charging pad. The civil works to install the system underneath the roads are large, and the system requires standardization across EVs.

Figure 5.11 Wireless charging while driving: vehicle rendering

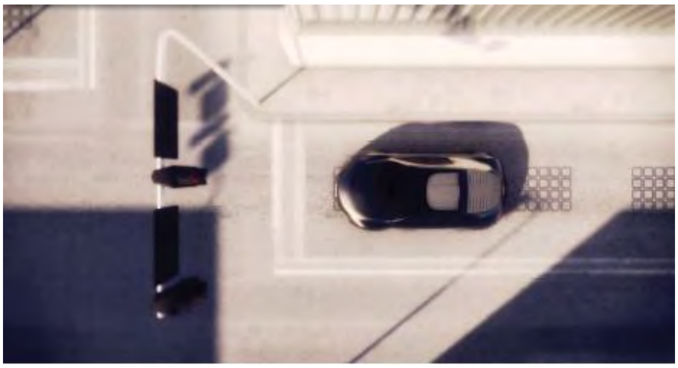

Figure 5.12 Wireless charging while driving: charging pads rendering

To wrap up this lecture, wireless charging of EVs is a convenient technology for charging electric vehicles. In case inductive power transfer, two charging pads, one in the ground and one underneath the vehicle are used to exchange power using magnetic fields. Power is exchanged at high frequencies in the order of 85 kHz, and power electronic converters are used to facilitate this. At extension of wireless charging is called on-road charging and allows EVs to be charged while they are driving by placing charging pads underneath the roads.

Practice problems

Question 1

Inductively coupled power transfer is based on the principle of:

- *Electromagnetic induction at high frequency*
- *Conduction*
- *Electromagnetic induction at grid frequency*
- *Capacitive power transfer*

Question 2

In a coupled inductor system in air, compensation capacitors are used for:

- Increasing the amount of reactive power drawn from the supply
- Reducing the voltage ripple on the EV battery
- Supplying reactive power to and from the primary and secondary windings
- Reducing the operating frequency of the IPT system, thus reducing the losses

Question 3

What is the range of values for the coupling coefficient (k) for IPT system in an air core configurations?

- 0 to 0.4
- 1 to 10
- 0.95 to 0.99
- 0.8 to 1

Question 4

Which of the following statement are true? Please note that more than one answer may be possible.

- ☐ If there is no compensation in an inductive power transfer system, a large amount of reactive power is drawn from the source to provide the reactive power of the leakage inductance.
- ☐ In the case of a inductive power transfer system, the coupling ratio is low, i.e. k<0.4 and therefore the mutual inductance is much higher than the leakage inductance.
- ☐ SAE J2954 standard for EV charging earmarks a small band between 80 – 90 kHz for wireless charging of EVs with a center frequency of 85 kHz

5.3 Battery swap

The following questions will be introduced in this lecture: what is battery swap technology? What are the advantages and disadvantages of battery swap? Fast charging and battery swap, which one is better in what perspective? And finally, what is the suitable application case for battery swap?

First of all, let's recall what battery swap is. The battery swap works on the basis of switching out the depleted battery and replacing the same with a full battery. The process involves driving into a battery switching bay, and an automated process will position the vehicle, switch out the current battery and replace it with a fully charged battery. The depleted batteries are charged in the station for later deployment.

Battery swap has plenty of advantages. Battery swap can provide a new fully charged battery, without the need to wait for the charging duration. In this case, the range anxiety is eased, and to some extent, infinite mileage is obtained. Batteries are charged outside the vehicles, so there is no limitation on the size, weight and power levels of the charger. Batteries are left being charged in battery swap station, which provides high flexibility on the charging power as well as charging time. Batteries can be charged according to the local load. Besides, battery swap only requires a few minutes, waiting anxiety is significantly eased. However, there are still quite a lot challenges for the market to accept battery swap. First, a Standardized Battery Interface is required across EV manufacturers and battery swap stations. Second, it is not easy for the consumers to accept not owning a battery. Third, there should be a fool-proof way to estimate the batteries state of health to check for its usage pattern. Finally, the frequent connection and detachment of the connection between the battery and the vehicle may cause safety issues.

Both battery swap and fast charging are hence two possible ways for quick charge replenishment. Now we are going to compare the battery swap with the fast charging based on the number of visits, the serving unit, waiting time, etc.

First, let's have a look at the number of visits. In order to get your car charged with fast charging, or to replace your car's battery with battery swap, you need to go to a charging station similar to refilling your car tank at the petrol station. In Figure 5.11, you can see the average number of charging station visits required per vehicle per year versus electric vehicle range in the Netherlands [4], based on research from the Dutch EV mobility survey of 2009. There are 19 different scenarios that are defined according to the different electric range of vehicles, shown on the x-axis. The lowest range is 80 km, while the highest 170 km, and the ranges increasing by 5 km. The average number of visits is always lower for the battery swap compared to fast charging. This is because more energy is transferred per battery swap compared to fast charging. The reason is that a battery can be fast charged only upto 75-85% state of charge and beyond that the charging power is limited. On the contrary, you always leave the battery swap station with a full battery with 100% state of charge.

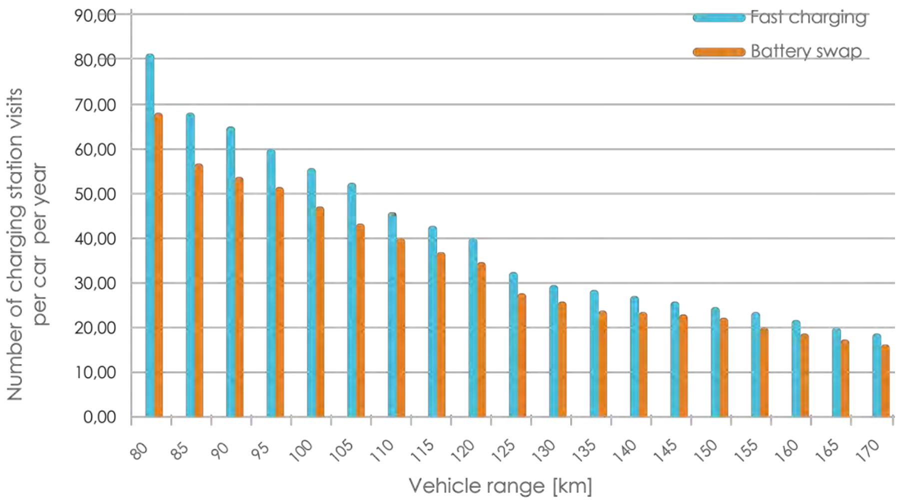

Figure 5.11 Number of visits to fast charging and battery swap stations

Fast charging provides a charging power normally higher than or equal to 50kW, and it may cause a severe impact on the grid especially when it's peak time when multiple cars are charging. On the contrary, the charging processes at a battery swap station can be shifted in time and can be controlled. One commonly applied charging power is 3 phase 11kW power. In terms of service time, fast charging requires different time duration depending on the charging power, the capacity of the battery whether the battery has to be partially or fully charged. Here are two examples. Assuming it is an ideal case and the fast charging power is 50 kW, it may cost you 11 minutes to finish charging your car for a range of 80km. However, it will cost you 22mins or twice as much if a range of 160 km is needed. On the other hand, battery swapping always has a fixed service time which could be 5 minutes or even less.

In reality, you may not always get a battery swap or a fast charging when you arrive at a charging station and would need to wait. Just as a petrol station, an EV charging or a battery swap station also has a limited capacity. We performed a study where queuing theory is used to compare the operation of a battery swap and fast charging station. A scheme for queuing theory is provided in Figure 5.12. The key factors considered that can influence the operation are:

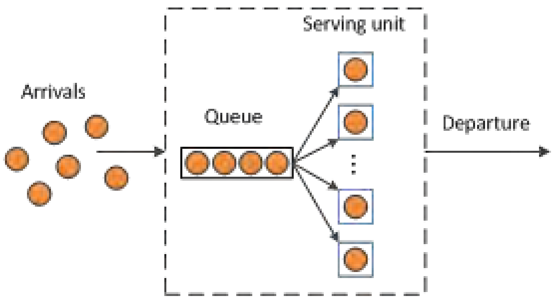

Figure 5.12 Queuing theory scheme

- The arrival of customers: this includes the distribution of the arrival times and the time interval in between.
- The behavior of customers: for example, are the customers willing to wait or leave after a short time?
- The service times: in this case, it is the charging time for the fast charging and the time for the battery replacement.
- The service discipline: here are many possibilities of service discipline like first come-first served, random order, last come first served, priorities, etc. Usually, we consider first come-first served order for this analysis.
- The number of service units: this is the number of fast charging points/ battery swap lanes. The service capacity is a trade-off between providing sufficient service while maintaining maximum utilization.
- The last factor is the waiting room: there can be limitations concerning the total number of customers that can be served. The arriving customers could be rejected if both the serving capacity and the queue are full. In the case of electric cars, the total amount of parking spaces can be considered as the waiting room.

First, let us compare the waiting time of fast charging and battery swap. The factors that influence the waiting time of fast charging are the required vehicle range, the charging power and the number of charging port at the station.

On the other hand, the main factors that influence the waiting time for battery swap are the battery capacity, the number of battery swap lanes, the number of batteries in the battery swap station, the charging power for the depleted batteries, and the number of charging port.

According to the queuing theory, the average waiting time per customer can be seen as a function of the number of serving units for a certain EV range. Figure 5.13 shows the averaged waiting time versus number of serving unit for three different quick charge replenishment cases. The first is Fast charging-Absolute Worst Case. It means to charge the battery from the minimum driving reserved range SOC, which is an equivalent 10km range, to 80% SOC. The

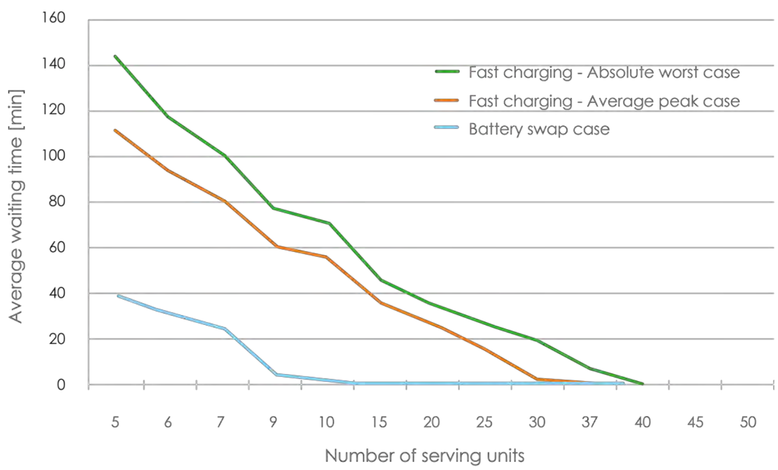

Figure 5.13 Waiting time for fast charging and battery swap

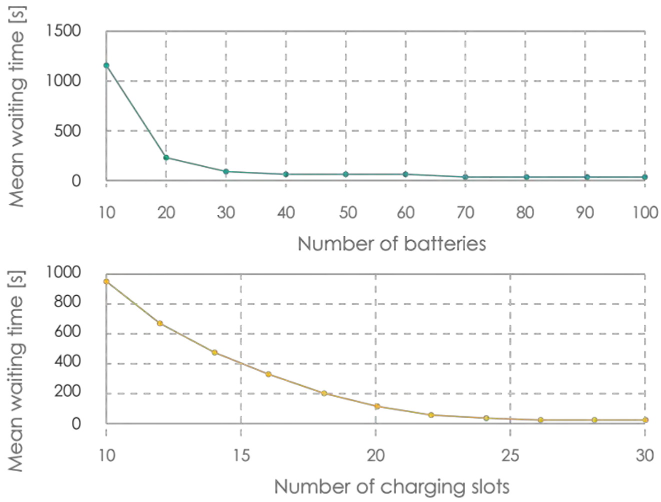

Figure 5.14 Waiting time for fast charging and battery swap

second is Fast charging-Average Peak Case, which is to fast charge the car in the evening peak based on driving energy needs. The third case is for battery swap. It can be seen the Figure 5.13 that to have the same waiting time for 125km range EV, battery swap requires much less number of serving units than fast charging. That is because battery swap needs much less serving time compared to fast charging

For battery swap, the waiting time can also be considered as a function of the number of batteries as well as the number of charging slots inside the battery swap station if other conditions are fixed. Figure 5.14 is one numerical result from a queueing network research from Hong Kong [5]. From these two graphs, we can see that the mean waiting time is very sensitive to the number of battery and it decreases to zero sharply when the number of battery increases. However, the mean waiting time decreases more gently with respect to the number of charging slots. It is clear from the graphs that after a certain point, there is no reason to further increase the number of serving units, the number of batteries or the number of charging slots inside a battery swap station to reduce waiting time.

Referring back to the research for the Dutch scenario, we can look at the optimum number of serving units in a quick charge station versus vehicle range with 10 minutes considered as the acceptable waiting time in the queue.

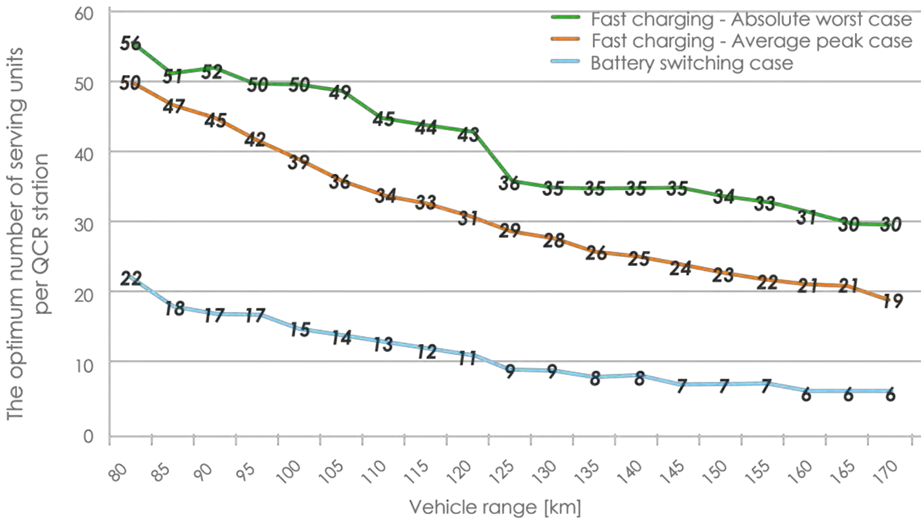

Figure 5.15 Number of serving units needed for fast charging and battery swap

From Figure 5.15 we can see the decreasing trend in the number of serving units required as vehicle range increases. However, the decreasing trend is significantly different for each of the three cases of charging technology and strategy. Vehicles with higher range need less number of visits per year to quick-charge station, and it decreases the arrival rate per station. So lower number of serving units can handle the charging needs. For the fast charging - Average Peak Case, significantly lower number of serving units are required. This is because the charging energy and charging time for the Average Peak Case is always lower than that of the Absolute Worst Case. Therefore, one serving unit and subsequently the whole station can serve more cars in a certain time. This means that the whole station can handle the same traffic behavior with a lower number of serving units. Finally, only about one-third of the serving units is needed for Battery Switching Case. Since the serving time is significantly lower for battery swap, which is about 5 min, the same traffic can be handled with less number of serving units at the battery swap station.

Another key factor to be considered for battery swap is the extra number of batteries required for satisfying the travel profile. For a battery swap scenario, batteries are required on-board the vehicle for driving and extra batteries are needed at the station for charging and to be kept ready for a swap. On the contrary, fast charging does not require extra batteries. In the research for the Dutch scenario, it was assumed that 10 minutes is the average waiting time in the queue, the charging power in the swap station is 10.8kW, and each simulation for battery swap was started with 80 percent extra batteries. The graph in Figure 5.16 shows the number of batteries that have always been fully charged and ready to be swapped at the battery swap station as a function of EV range. Depending on the arrival rate of the EVs, these “always fully charged batteries” can be considered excessive and part of them are not necessary. From this graph, it can be seen that for an EV fleet with higher range and larger battery capacity, a lesser number of fully charged batteries are ready at the swap station as the batteries with higher capacity need longer time to be re-charged to full. Then, the percentage of batteries that are waiting for charge or in charging process versus EV range in the swap station is shown in this purple curve. This is simply calculated by 80%, the simulation

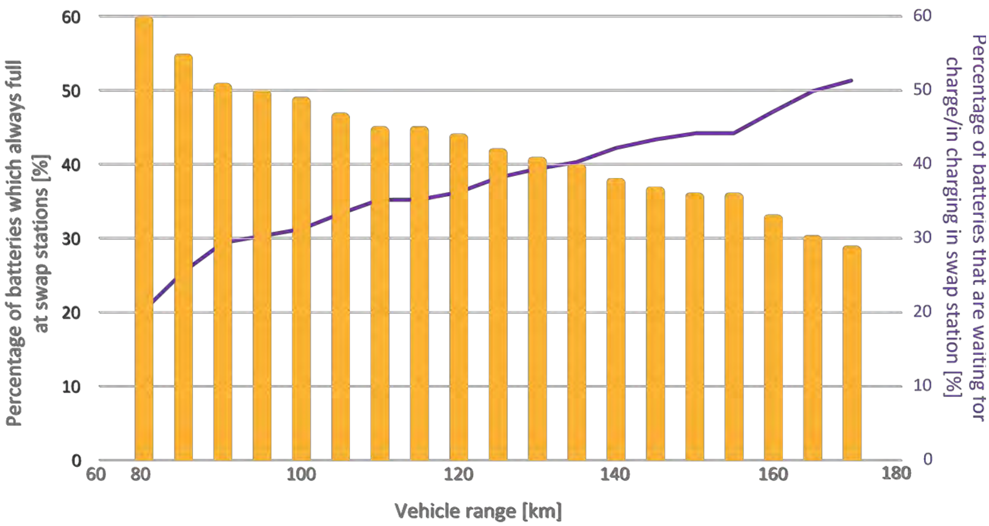

Figure 5.16 Extra batteries per car

point, minus the number of batteries that are always fully charged, which is the orange bars. This indicates that more minimum overall extra batteries are required in the battery swap station if the EVs have higher range.

With both a qualitative and quantitative understanding of battery swap, we are now going to introduce a few application cases. Let us consider Figure 5.17. The first example is that of fixed route logistics. Assume there is a supermarket chain in the city, a few distribution centers responsible for distributing goods to each store via a delivery truck fleet. In this case, the delivery trucks can be electrical, and each distribution center can be equipped with battery swap facilities. Whenever the electric trucks get back to the distribution centers, they have a chance to get their batteries swapped if necessary. The second application example is public transportation where the bus fleet normally commutes between fixed destinations through fixed routes. This also makes it quite convenient and suitable for battery swap implementation where the electric buses can swap their batteries in the central bus station or one of the destinations where there is a swap facility available.

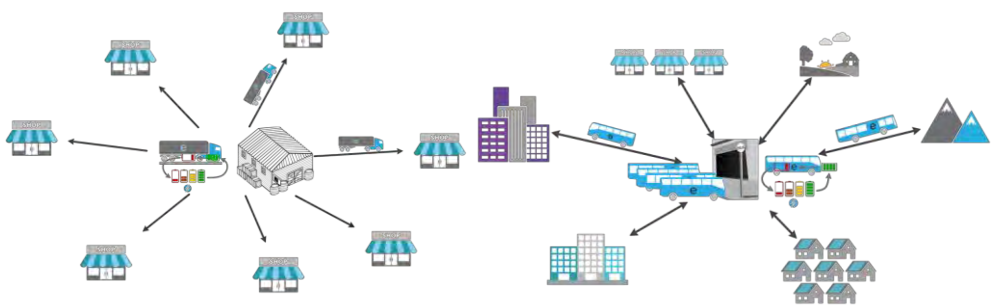

Figure 5.17 Battery swap applications: fixed route logistics (on the left) and public transportation (on the right)

To wrap up. You have now got an idea of what battery swap is and what are its advantages and disadvantages. We looked into the comparison of fast charging and battery swap in detail based on queuing theory. Two application examples of the battery swap were introduced where fleet managers can use battery swap for quick recharge of EVs, especially for fixed route movement of vehicles.

Practice problems

Question 1

EV 1 and EV 2 have a battery of 50 kWh and 100 kWh, respectively and they both come to a battery swap station.

a. The battery swapping service time for EV 1 to swap the empty battery and to replace it with a fully charged battery is:
   - o Double of that of EV 2
   - o Half of that of EV 2
   - o Is more or less the same as EV 2

b. The time taken in the battery swap station to charge the battery of EV 1 from an empty state to a full state is:
   - o Double of that of EV 2
   - o Half of that of EV 2
   - o Is more or less the same as EV 2

Question 2

Based on queuing theory, how can the mean waiting time (not the service time) at a battery swap station be reduced? More than one answer is possible.

- ☐ By Increasing the number of batteries at the station
- ☐ By Increasing the number of battery swapping bays (serving units)
- ☐ By increasing the length of the queue at each station
- ☐ None of the above

Question 3

Based on queuing theory, the number of fully charged batteries that are ready to be swapped at the battery swap station reduces:

- o As the vehicle range increases
- o As the vehicle range decreases
- o Vehicle range has no influence

5.4 Charging EV from renewables

The following topics will be introduced in this lecture. First, why do we need to charge electric vehicles from renewable sources of energy? Second, what power converters are needed for charging electric cars from PV and wind? And finally, how can we implement smart charging of EVs from renewable energy?

The main driver for moving to electric vehicles is because they have no tailpipe emissions and are more efficient than combustion engine cars. However, electric vehicles are only sustainable if the electricity used to charge them comes from renewable sources of energy and not from fossil fuels.

In Figure 5.18, we can see the equivalent carbon dioxide emissions from a lifecycle assessment which includes the emissions due to vehicle production, the well-to-wheel emissions for the fuel, vehicle maintenance and end-of-life recycling of the vehicle [6]. The graph has three parts:

- The emissions for different combustion engine cars are shown on the right side
- The middle part shows the emissions for battery electric cars charged from different emitting electricity generation sources
- The left part shows the emissions for battery electric cars charged from different non-emitting (maybe renewable) electricity generation sources.

We can clearly see that electric vehicles have far lower emissions from a lifecycle perspective even when charged from an electricity grid dominated by fossil fuels. However, if the electricity itself is generated from non-emitting sources like wind, hydro or nuclear, then the net lifecycle emissions of the electric vehicle are further lowered and well to tank emissions become zero. It is hence necessary to use renewable sources of electricity to charge electric cars in the future.

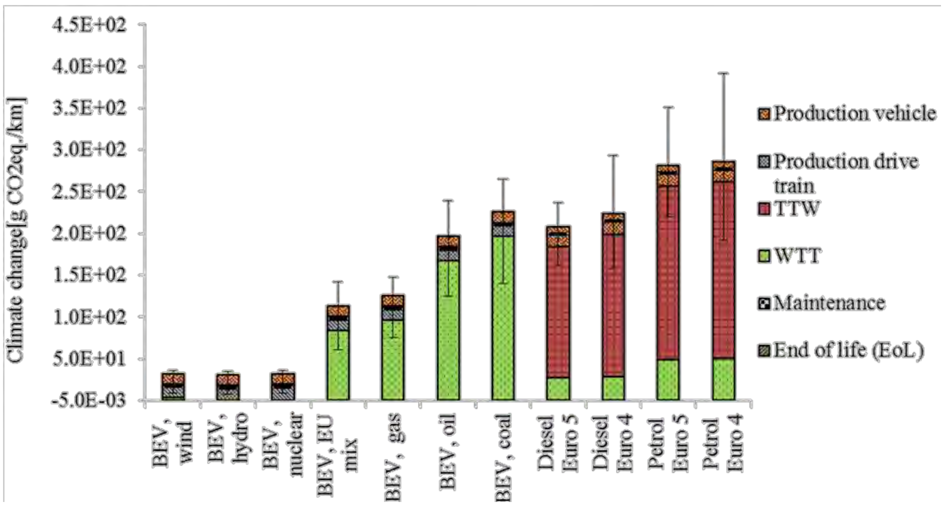

Figure 5.18 Climate change impact from lifecycles of different car technologies

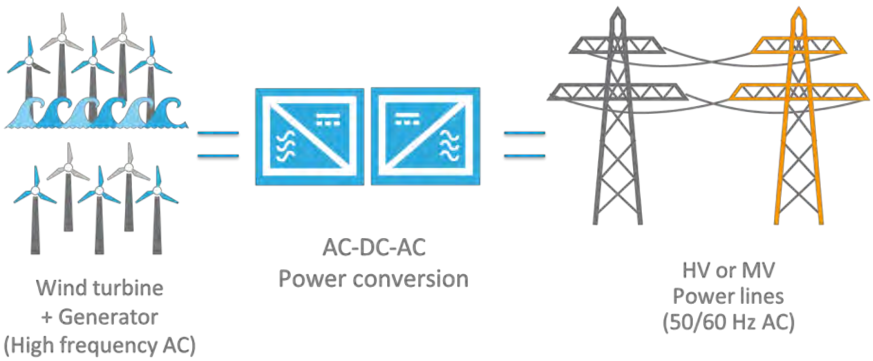

Figure 5.19 HVAC wind energy grid connection

Now, let us look at how we can develop an EV charging system powered by wind and solar energy. In case of wind energy, as seen in Figure 5.19, three key factors play a key role in the design of the charging system. First, wind power is typically generated today using on-shore or off-shore wind farms that are located far away from where electric vehicles are charged. This means that the power must be transported long distances between the supply and the EV load. Second, a wind turbine is typically rated in the order of megawatts while an EV charger is normally working in the order of kW. This shows the big difference in power scales and the potential of one wind turbine to charge several hundred cars. Finally, wind generation is maximum in winter and in the night time. Hence, wind generation is ideally suited for charging electric cars at homes in the night.

From a power conversion perspective, generators used in wind turbines typically produce variable frequency AC power. Two back to back AC-to-DC and DC-to-AC power converters are used to convert the variable frequency AC power to high voltage or medium voltage 50Hz or 60Hz AC power used for long distance power transmission. This power is then stepped down to low voltage AC power, and the EV can then be charged using AC or DC charging, as depicted in Figure 5.20.

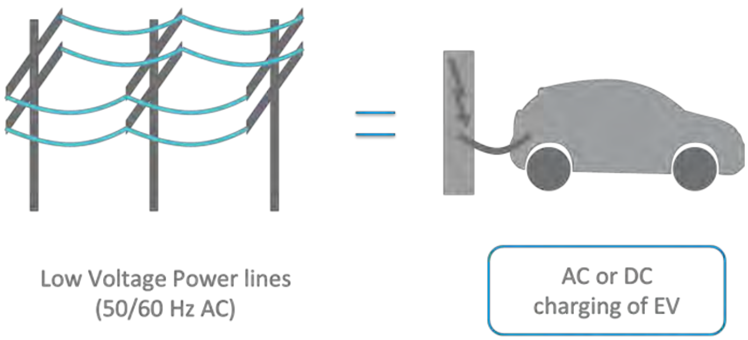

Figure 5.20 Low voltage AC or DC charging of EV

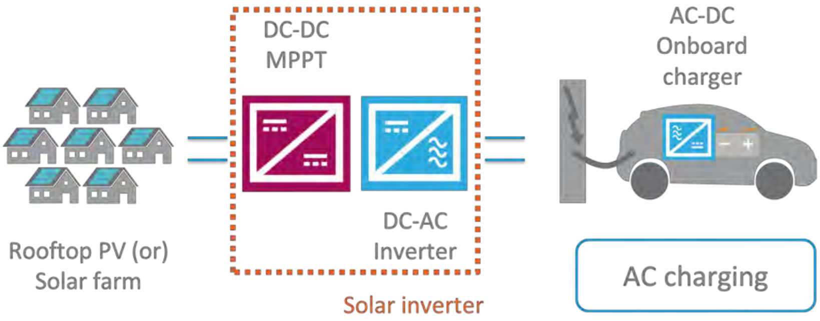

Figure 5.21 Charging EV from solar energy: AC charging

On the other hand, things are a bit different when charging electric vehicles from solar energy. First, solar panels have the benefit that they can be installed on the rooftop of buildings, besides being installed as solar farms. Therefore, solar power can be generated close to where electric vehicles will be charged, thus reducing the transmission losses. Second, rooftop solar PV systems are typically rated in the order of kilowatts which is similar to the power rating of an EV charger. Finally, in contrast to wind generation, solar generation is maximum in the daytime and in summer. Hence, solar generation is ideally suited for charging cars at workplaces during the day.

The simplest way to realize a solar powered EV charging station is to use a solar inverter. A DC-to-DC power converter operates the solar panels at the maximum power point. Then, a DC-AC inverter converts the DC power to 50Hz or 60Hz AC power for AC charging of the EV. There is, however, one disadvantage with this method, as you can see from Figure 5.21. Photovoltaic panels and the EV battery are both fundamentally direct current or DC by nature. And in this method, the DC power is unnecessarily converted to AC and back. Hence, a more efficient way to charge EV from PV is to use an isolated DC-to-DC converter and directly charge the EV from PV using DC charging, as exemplified in Figure 5.22.

For example, at the Delft University of Technology together with our partners PRE and LMS, a 10kW solar powered DC charger has been developed [7]. It has three power converters, a DC-to-DC converter for the solar panels, a DC-DC isolated converter for the electric car and a DC-to-AC inverter to connect to the AC grid. Using this design, shown in Figure 5.23, direct DC

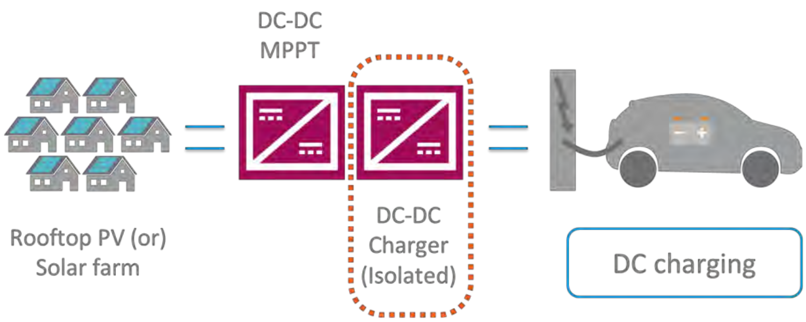

Figure 5.22 Charging EV from solar energy: DC charging

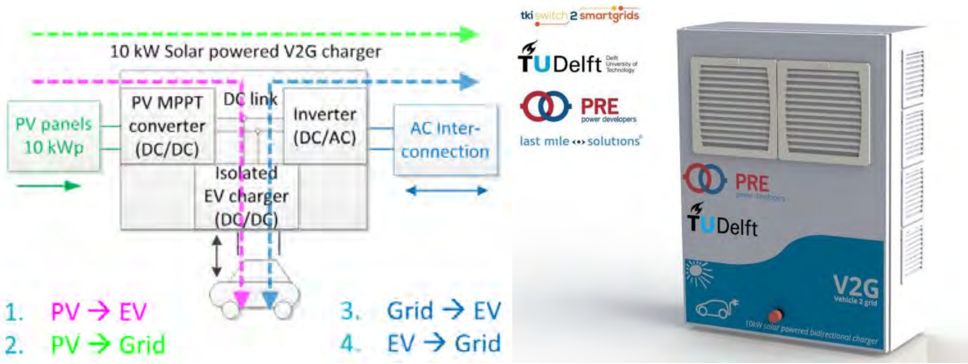

Figure 5.23 TU Delft and PRE design for a DC-DC converter to enable V2G technology

charging of EV from PV can be realized. Secondly, if there is no electric car, then the system acts as a solar inverter and feeds PV power to the grid. Third, if there is no solar power, the system operates as a conventional DC charger and charges the EV from the grid. Finally, the charger is bidirectional and capable of vehicle-to-grid. So the EV can not only charge from the grid, it can feed power back to the grid as well.

The unique aspect of combining solar charging and vehicle-to-grid is that the electric car battery can now be used as a storage for renewable electricity. Imagine a scenario where your car charges itself at the workplace from solar energy and powers your home in the evening using V2G! Of course, the main challenge with powering electric cars from renewable energy is the variability in generation.

For example, in the graph given in Figure 5.24, we can see the daily energy yield of a 10kW PV system in the Netherlands for one year showing the seasonal variation in generation. It is interesting to note that the daily yield can range from 1 kWh all the way up to 75 kWh over the year. What this means for EV charging in the Netherlands is that you can charge less than half of a 30 kWh battery of a Nissan Leaf EV in winter, about one Leaf in spring and about two Leafs in summer. Bear in mind that depending on the location and weather conditions, the

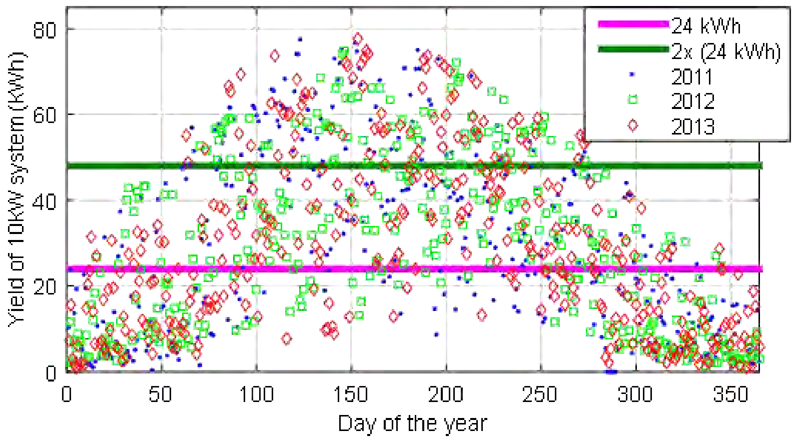

Figure 5.24 Variability in renewable generation: PV generation in the Netherlands

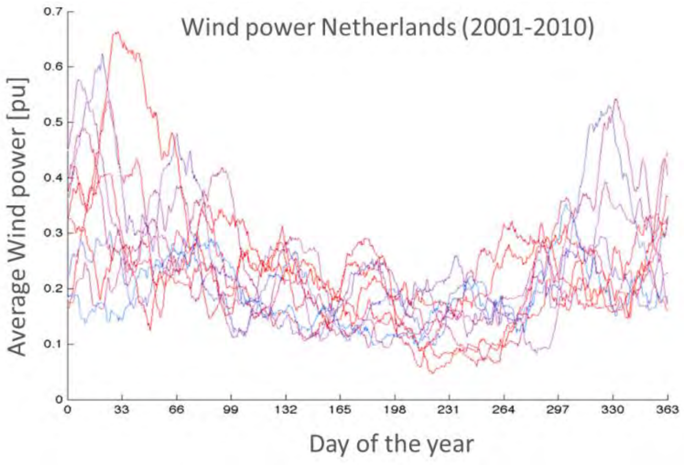

Figure 5.25 Variability in renewable generation: wind generation in the Netherlands

situation can be much better or worse than this. But, there will always be diurnal and seasonal variation in generation. Wind generation, on the other hand, shows an inverted U variation as shown in Figure 5.25 of average wind power for the Netherlands over the year.

A solution to overcome this variation is to size the wind and solar installation such that we are guaranteed of sufficient energy even when the sunshine and wind are minimal. The disadvantage is that this can cause overproduction and wastage of power when the solar insolation and/or wind speeds are maximum. For example, in the graph of Figure 5.26 we see the fraction of total renewable energy lost when different combinations of wind and solar are installed [8]. The left side corresponds to a scenario with 100% wind generation, and the right side corresponds to 100% solar generation. What the graph shows us is that the key to reducing the energy lost is to install an optimum combination of both wind and solar energy so that the day-night and summer-winter differences in power production between wind and solar are balanced

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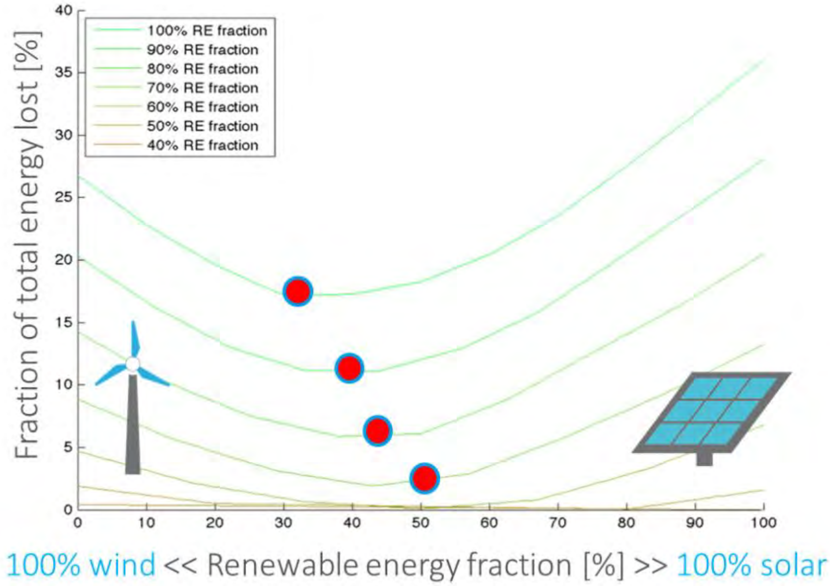


Figure 5.26 Optimal combination of wind and solar

Table 5.4 Control PWM on control pilot of AC charger based on PV or wind generation

Advantages	Disadvantages
Aesthetically favorable, no vandalism	5-10% higher losses
Safety	Higher costs compared to AC, DC charging
Comfort	Extra converters compared to AC charging

A second solution to help match renewable generation and EV charging is smart charging. When the solar and wind generation is high, the EV charging power can be increased and vice versa. This has the dual benefit of making EVs sustainable by using more green energy and reducing the stress on the grid due to large-scale renewable energy generation. In case of AC charging, as summarized in Table 5.4, the pulse width modulation signal on the control pilot of the Type 1 and Type 2 AC chargers can be continuously controlled to adjust the EV charging current based on solar or wind generation. For CHAdeMO and combo DC charging, CAN and PLC communication can be respectively used to adjust the charging power.

Looking at 5.27, the duty cycle of the pilot signals communicate the maximum current the electric vehicle service equipment (EVSE) is capable of supplying to the vehicle, I_{max}. The vehicle can then draw a charging current $I_{ac} \leq I_{max}$. The relationship between PWM duty cycle (in %) and current Imax is defined by two different equations depending on the current range specified:

For a 6A to 51A service: $Duty\ cycle = I_{max}/0.6$ (5.7)

For a 51A to 80A service: $Duty\ cycle = I_{max}/2.5 + 64$ (5.8)

To demonstrate this relationship further, Table 5.5 shows some of the common current ratings.

To wrap up, in this lecture we looked at why electric cars in the future must be charged from sustainable sources of electricity like wind and solar. We look at the power conversion required for solar and wind-based EV charging systems. Two methods can be used to overcome the variability in renewable energy generation. One is to use an optimal combination of wind and solar energy so that they can help balance each other. The other technique is to implement smart charging of EV based on renewable energy generation.

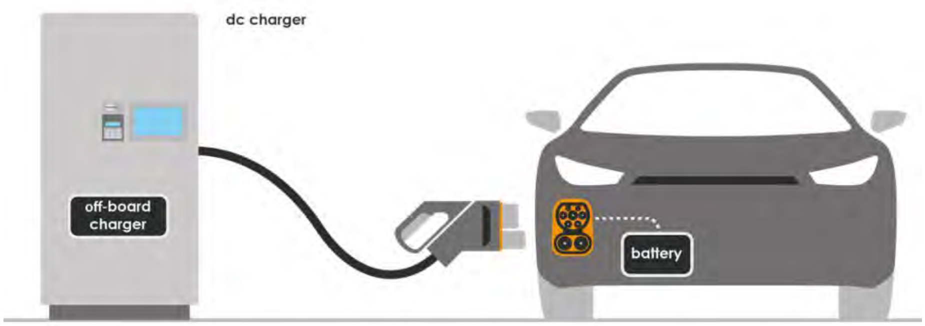


Figure 5.27 AC charging: Type 1 and Type 2 PP and CP schemes

Table 5.5 AC current ratings and Duty cycle of PWM

AC Charging current	Duty cycle of PWM on CP
5	8.3%
15	25%
30	50%
65	90%
80	96%

Practice problems

Question 1

Why should EVs be charged from PV panels on DC instead of AC?

- EV and PV panels are both DC by nature
- DC power transfer is cheaper than AC
- DC cables have lower copper losses than AC cables
- AC charging of EV cannot be done at fast charging power levels

Question 2

Consider whether the following statements are true or false:

A. Electric vehicles have zero tank to wheel emissions. But, they can have significant well to tank emissions depending on the source of electricity generation.

B. In case of AC charging, the pulse width modulation signal on the control pilot of the Type 1 AC charger can be continuously controlled to adjust the EV charging current based on wind generation.

- Both statements A and B are false
- Statement A is true, statement B is false
- Statement A is false, statement B is true
- Both statements A and B are true

Question 3

Here below you see a paragraph about renewable energy generation. Choose from the options below to correctly fill in the blanks. These options can be used more than once.

The options are: **wind generation**, **solar generation**, **day**, **night**.

_______________(1) is maximum in winter and in the _______________ (2) time. Hence, _______________ (3) is ideally suited for charging electric cars at homes in the _______________ (4). On the other hand _______________ (5) is maximum in the _______________ (6) time and in summer. Hence, _______________ (7) is ideally suited for charging cars at workplaces during the _______________ (8).

Question 4

In an AC charger, the PWM pulse on the control pilot is such that it corresponds to a AC charging current of 32A. What can the magnitude of charging current drawn by the EV be?

- Always equal to 32A
- Always greater than or equal 32A
- Always less than or equal to 32A

5.5 Case Study: Nuna Solar car

Now that we have learned about the technical aspects of EV's, it seems obvious that the most straightforward way of powering a car is by using PV panels that direct power the electric motor. A prototype car with built-in solar panels has was first built in 1982 by Hans Tholstrup, who later conceived a race called the World Solar Challenge, which is a biennial race stretching 3000 km from North to South Australia.

The Nuon Solar Team of TU Delft have been starting this race since 2001 and they have a pretty impressive track record. This dream-team have won seven times and have come in second the other two times they competed. So what does it take to build a solar car, and how is it different from a normal EV? How can you make it the best in the world?

Today we visit them and talk with **Jelmer van der Hoeven**, who is an electrical engineering student working on the car, called the Nuna 9S.

We build solar cars to race in solar races. We race in Australia where we do the world solar championship and in South Africa where we race in the Sasol Solar Challenge. And by doing this we hope to promote sustainable energy.

What is different about Nuna compared to a normal EV?

Well, Nuna, an electric vehicle, only uses the power from the power supplies from the power outlet and use the power from the sun, which is the main difference. But, also how we use the output from the energy is also very different, because we want to maximise the power input from the sun and want to minimise the power that we choose to race. And, we minimise it by a couple of things. First, the drivetrain. A normal electric vehicle uses a shaft, which is powered by an electric motor and we use an in-wheel electric motor, which we only use one: the right rear wheel. And, by using only one motor we also save weight. And you don't have the losses from the shaft. This is on the drivetrain. We also have the air resistance and rolling resistance. The rolling resistance is minimized by choosing as light weight material as possible. Our own car is built from carbon fibres. Carbon fibres are very stiff and very strong. So, their weight to stiffness ratio is very high and that it is why it is a very good material for us to build our body. An electric vehicle is about 1500-2000 kg and our newest Nuna9S weighs only 140 kg, so that is very amazing that we can get such a low weight car.

And that really impacts the driving range I imagine?

Yes, our driving range without the solar panels is around 500 km and we have 5 kWh battery. And if you compare that to a Tesla which can also reach to about 500 km than the battery weighs around 500 kg and our battery weighs around 20 kg. So, that is a huge difference.

How has Nuna evolved over time?

The first generation Nuna was a lot bigger. The solar panel was from the same kind of solar cells: Gallium Arsenide. But, they were recycled solar cells from a Hubble Telescope and they had around 8 m^2 of solar cells and our newest, the Nuna9S, has around 2.6 m^2 of solar cells. And, also regulations have changed. The solar area was one of those regulations, but also the first Nuna was a three-wheeler and the regulations are now so that it has to be a four-wheeler. And, the challenge in that is that the three-wheeler had a good balance and with the driver now sitting at the right side of the car and not in the middle, the balance is a lot harder to improve.

What are you improving on for the Nuna 9S?

That is still a little bit secret what we are working on right now. We have a new software engineer who is working on a new board computer, which will make it more intelligent, our vehicle.

Can you quickly walk us through the energy flow in the Nuna?

Yes, we can separate it in 3 parts. The income part, the storage part and the expense part. We start with the income part. We have a solar array, which generates electricity, and to make it sure that the solar cells are working at their optimum point, we have maximum power point trackers. And what these maximum power trackers do, is to make sure that the maximum energy is generated from our solar array. And, this is the I-V curve of a solar cell and what the MPPTs do, is to make sure that the maximum power is always reached. And, it does it by sweeping around the voltage line, where it checks at what point/at what voltage, is the most energy flowing out of the solar array. And, from the maximum power point tracker the energy is flown through the battery, where we store our energy. The battery, as I told, was 5 kWh. They are made of Lithium-ion cells and we make everything ourselves from the battery pack to make sure that the battery is monitored and keeping at the good temperature. We have a battery management system to protect our battery, so that we know at what voltages all the cells are and that we know if some errors appear that we can act on that. And, also inside the storage we have the high voltage that is coming out of the battery, but also lower voltage that is made through our DC-DC converter. From the high voltage, the motor controller and the motor. The motor controller makes sure that the right gas response is given to the motor. And, it does it through three phase connection to the motor and with the changing currency from the motor controller the motor creates an electric force, which drives our car. And from the low power side/from the lower voltage, is given to the board computer, which is the central communication hub in our car. And this, the steering wheel is connected to it. Everything is connected through the board computer, which collects all the data. Further, we have also lights, so that we can make sure that if we want to break, the rest of the vehicles at the road know what we are doing. And we have also communication, because we have also cars driving around us, so that we can communicate to. Our strategist, also in the car, which says at which optimum point, at which optimum speed, we need to drive.

And if we use this in a race in Australia, what would be a typical income from the solar array in terms of power?

That is around 1 kWh.

And the maximum power output of the motor?

The maximum out-power of the motor is 5 kW, so if you need to accelerate than you also use the power from the battery.

And if it is stable going at maybe 90 km/h?

It depends a little bit on the weather conditions, because if we have side winds our car is so designed that is has a little bit like a sailing effect. So, that is drives the car. And, at 90 km/h it

And if it is stable going at maybe 90 km/h?

It depends a little bit on the weather conditions, because if we have side winds our car is so designed that is has a little bit like a sailing effect. So, that is drives the car. And, at 90 km/h it could be possible that we are energy neutral.

How do you foresee the Nuna to be in 2030?

I think it will be more like a normal passenger car due to the regulations and also, because it is still a race car that will evolve over time. And, it will be more intelligent, so that it can do strategy: at what speed it the best should drive from the weather conditions. That can determine it itself, because now we have a special car driving behind Nuna, which calculates all weather predictions, all the calculations from what is the best speed to drive and other things that is calculated in a car behind Nuna. And, that will probably be done inside of Nuna.

Do you foresee PV cars to become commercialized soon?

I think people will eventually drive with solar cells on their roof. Eventually, it will mainly increase the range for now. But I think in highly solar adoration places, they have enough solar power to drive their daily uses.

Summary

We have now seen many key technologies that will make electric cars cleaner, more sustainable, convenient and safer to drive in the future. In the first lecture, we briefly looked at the important technologies and emerging trends in electric vehicles and charging infrastructure design. We then discussed the concepts of solar electric vehicles and fuel cell electric vehicles. Finally, the lecture concluded with autonomous electric vehicles and how it can open up a plethora of opportunities in the future such as shared and connected mobility, cities decongested of cars and parking spaces, higher utilization of vehicles, lower cost of mobility and more efficient point-to-point connectivity.

In the second lecture, we looked in detail about wireless charging of electric vehicles. In the case of inductive power transfer, two charging pads, one in the ground and one underneath the vehicle are used to exchange power using magnetic fields at high frequencies in the order of 85 kHz. Power electronic converters are used to facilitate the DC-DC and AC-DC power conversion required. The extension of wireless charging called is called dynamic on-road charging and it allow EVs to be charged while they are driving by placing charging pads underneath the roads.

The third lecture of the module started with a detailed introduction to battery swap and its advantages and challenges. We then looked into the comparison of fast charging and battery swap in detail based on queuing theory. Battery swap has a definitive advantage due to the shorter service time and ability to smart charge the batteries at the swapping station later on. A specific application for battery swap is where fleet managers can use battery swap for quick recharge of EVs, especially for fixed route movement of vehicles. However, the key challenge for battery swap to be successful is that EV manufacturers must agree on a common platform for battery and battery interface so that swapping stations can cater to a wide variety of vehicles.

In the fourth lecture of the module, we looked at why electric cars in the future must be charged from sustainable sources of electricity like wind and solar. Solar charging of EV has the fundamental advantage that rooftop PV installation can be installed in close proximity to where EVs can be charged. Finally, we discussed about the two methods that can be used to overcome the variability in renewable energy generation. One is to use an optimal combination of wind and solar energy so that they can help balance each other. The other technique is to implement smart charging of EV based on renewable energy generation.

Let's look at it in this video made by Nissan Motors on how future cities will look like with EVs as the "Fuel station of the future".

And let us look at this vision for future highways with dynamic on road charging and powering of vehicles by wind and solar energy. We thank TU Delft alumni Natalia Scheele who made this video as part of her MSc thesis on green energy highways for future autonomous electric vehicles.

Practice problems

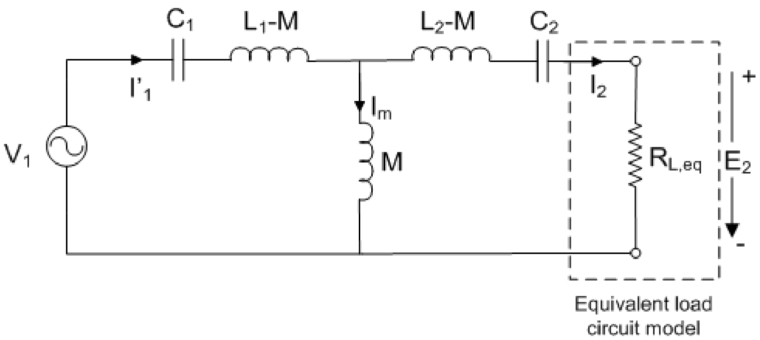
Question 1

What is the use of an aluminium backplate in an inductive power transfer system? More than one answer is possible.

- ☐ Permits only unidirectional flux movement
- ☐ Acts as an magnetic flux shielding material
- ☐ Prevents the magnetic flux from penetrating below the ground
- ☐ Increases the efficiency of power transfer

Question 2

In an IPT system operating at 85 kHz, the self inductance is 500 µH and the leakage inductance is 400 µH for both the primary and secondary coil.



a. What is the mutual inductance based on the equivalent circuit shown?
   - o 500 µH
   - o 400 µH
   - o 100 µH
   - o 300 µH

b. What is the coupling coefficient?
   - o 1
   - o 0.2
   - o 0
   - o 0.4

c. What is the compensation capacitor needed on the primary side based on series-series compensation (nF, nanofarad)?
   - o 7nF
   - o 1nF
   - o 20nF
   - o 27nF

d. Let us compare the two coils inductive power transfer system with compensation and without compensation. Does the coupling coefficient (κ) and mutual inductance (M) change once compensation capacitors are added?
   - o κ and M increases and helps increase the efficiency of power transfer
   - o κ and M decrease and help increase the efficiency of power transfer
   - o No, κ and M do not change as they are dependent on how the coils are designed and not on the addition of the compensation capacitors.

Question 3

An EV user would like to charge his car using solar energy from his rooftop PV system. He uses a Type 2 connector on a 230V AC connection with a mechanism by which the PWM on the control pilot changes exactly so that the PV power and the EV charging power are equal to each other.

a. If the PV power generated at a certain moment is 10kW, what must be the duty cycle of the control pilot PWM on the EV charger?
- o 43%
- o 25%
- o 35.5%
- o 72.5%

b. If PV generation suddenly increases to 16kW. Then, what must be the duty cycle of the control pilot PWM?
- o 116%

- o 96%
- o 75%
- o 92%

Resources

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Final model quiz

Section 5.1

Question 1

Match the autonomous EV sensor and its characteristic.

Sensor:	*Characteristic:*
• GPS	• Read road signs
• Radar	• Monitor position of other vehicles

- Camera
- Lidar

- Accurate position of the vehicle based on satellite information
- Detect pulses of light that are bounced off the surroundings

Question 2

If the battery voltage of an EV is doubled from 400V to 800V, the charging current for the same charging power is:

- o Halved
- o Doubled
- o Remains unchanged

Question 3

Which are the following statements are **true** and **false**?

a. In level 4 autonomous driving, the car can autonomously drive itself in all conditions. ______

b. Smart charging can help reduce charging cost by charging cars at times of lower energy prices. ______

c. Integrating powertrain components in the EV makes the integrated components bigger in size, thus increasing the weight of the vehicle. ______

Section 5.2

Question 1

In a coupled inductor configuration, if the coupling coefficient k is very high (k >0.95), how does the leakage inductance compare to the mutual inductance? For simplicity assume that the coils on the primary and secondary side have the same self-inductance.

- o Leakage inductance is similar to mutual inductance
- o Leakage inductance is much lower than the mutual inductance
- o Leakage inductance is much higher than the mutual inductance

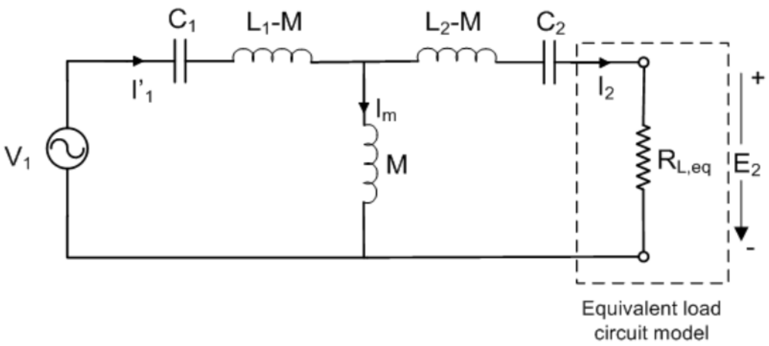
Question 2

What is the typical frequency at which inductive power transfer systems for EV charging are operated

- o 50-200 Hz
- o 40-100 kHz
- o 10-100 MHz
- o 1-5 GHz

Question 3

In an IPT system operating at 85 kHz, the self inductance is 1000 µH and the leakage inductance is 600 µH for both the primary and secondary coil.



a. What is the mutual inductance based on the equivalent circuit shown?

- o 500 µH
- o 400 µH
- o 100 µH
- o 300 µH

b. When an IPT system operates with compensation capacitors such that $\omega^2 = \frac{1}{L_1C_1}$ and $\omega^2 = \frac{1}{L_2C_2}$. Which of the following statements are applicable?

- o A resonance between the L-C components on the primary and secondary side
- o Current drawn from the source is purely used to provide the load power
- o The reactive power needed by the leakage inductances are provided by the compensation capacitors
- o All of the above

c. What is the compensation capacitor needed on the primary side based on series-series compensation (nF, nanofarad)?

- o 7nF
- o 3.5nF
- o 10nF
- o 12nF

Section 5.3

Question 1

Which of the following are the disadvantages of battery swap technology when compared to fast charging? More than one answer can be right.

- ☐ *Standardized Battery and interface is required across EV manufacturers*
- ☐ *It's not easy for the consumers to accept not owning a battery*

- ☐ *Frequent connection and detachment of the connection between the battery and the vehicle may cause safety issues*
- ☐ *Battery takes a long time to charge at the charging station*

Question 2

The average number of charging/swapping station visits is always lower for the battery swap when compared to fast charging because

- o Only 75-85% of the battery can be charged using fast charging
- o Battery swap takes shorter time to provide a full battery than fast charging
- o Fast charging requires high charging power >50kW
- o Battery swap can use lower charging power than 50kW

Question 3

Two electric cars EV A and EV B depart on a trip from Los Angeles to San Francisco, a trip of 600 km. The vehicles travel at 150 km/hr with an energy consumption of 200 Wh/km. The range of both the EVs is 400 km.

a. What is the battery capacity of the two EVs?
   - o 30 kWh
   - o 80 kWh
   - o 100 kWh
   - o 50 kWh

b. How many stops do the EVs need to complete the trip? Assume start the trip with a full battery, they charge when the battery becomes empty, can always find a charger when needed and the EV is fast charged up to its full capacity.
   - o 2 stop
   - o 3 stop
   - o 1 stop
   - o No stops

c. If EV A does fast charging using a 50 kW charger and EV B does a battery swap that takes 5 min, what is the total trip time for EV A and B, respectively? Assume here that the EV is fast charged up to its full capacity. ty.
   - o 8h, 4.08h
   - o 7.4h, 5h
   - o 5.6h, 4.08h
   - o 6.4h, 5.08h

Section 5.4

Question 1

What is the advantage when V2G and EV charging from renewables are combined?

- o Increased efficiency of renewable energy generation
- o EV can be used as a storage for renewable energy
- o Lower cost of electricity production

Question 2

In the chapter, we learnt about the 10kW solar powered DC charger developed by Delft University of Technology together with partners PRE and LMS. It has three converters and each of them have their own purpose.

Converter:	*Purpose:*
• DC-DC converter	• For solar panels with maximum power point tracking
• DC-DC isolated converter	• To exchange power with the AC grid
• DC-AC converter	• For electric car charging

Question 3

Consider whether the following statements are true or false:

A. The advantage of the above mentioned solar powered DC charger is that when there is no solar power, the system can operate as a conventional DC charger and charge the EV from the grid.

B. The benefit of combining solar charging and vehicle-to-grid is that the electric car battery can be used as a storage for renewable electricity.

- o Both statements A and B are false
- o Statement A is true, statement B is false
- o Statement A is false, statement B is true
- o Both statements A and B are true

Question 4

To control the AC EV charging current up to 30A in a Type 2 charger, what must be the PWM pulse on the control pilot?

- o 30%
- o 50%
- o 75%
- o 65%

Section 5.7

Question 1

Match the autonomous EV driving level and the corresponding features.

Level:	*Characteristic:*
• EV driving level: 0	• In certain conditions, the car controls either the steering or speed
• EV driving level: 1	• In all conditions, the car can autonomously drive itself
• EV driving level: 2	• In certain conditions, the car can steer, accelerate and brake
• EV driving level: 3	• No autonomous capability
• EV driving level: 5	• In many conditions, the car can manage most aspects of driving

Question 2

What are the main disadvantages of the inductive power transfer systems when compared to conductive charging? More than one answer is possible.

- ☐ Higher losses in the system
- ☐ Higher cost of the system
- ☐ Higher convenience of the system due to lack of cables
- ☐ Efficiency loss when there is a misalignment between the two charge pads on the ground and the vehicle

Question 3

Based on queuing theory, when is the optimal number of battery swapping serving units required reduced at the battery swap stations? More than one answer is possible.

- ☐ As the vehicle range increases
- ☐ As the vehicle range decreases
- ☐ As the arrival rate of customers reduces
- ☐ As battery kWh capacity increases

Question 4

In coupled inductor configuration, if the coupling coefficient κ is low ($\kappa < 0.2$), how does the leakage inductance compare to the mutual inductance? For simplicity assume that the coils on the primary and secondary side have the same self inductance.

- Leakage inductance is similar to mutual inductance
- Leakage inductance is much lower than the mutual inductance
- Leakage inductance is much higher than the mutual inductance

Question 5

Consider whether the following statements are true or false:

A. The advantage of using non-emitting sources of electricity like wind or hydro to charge electric cars as opposed to emitting source like coal, is that the net lifecycle emissions of the electric vehicle are lowered and the well-to-tank emissions become zero.

B. The Nuna solar race car uses only one in-wheel motor and no shaft in order to reduce the weight of the car and the associated losses in the shaft.

- Both statements A and B are false
- Statement A is true, statement B is false
- Statement A is false, statement B is true
- Both statements A and B are true

Question 6

Use the below plot from Figure 5.24 showing the variability in renewable energy generation to answer the questions.

a. What is the variation in daily yield over the year?
   - 1 kWh to 75 kWh
   - 40 kWh to 80 kWh
   - 30 kWh to 70 kWh

b. Assuming in the plot that days 250 - 360 and 0 - 100 represent winter season and the rest represent summer season, choose the correct statement:
   - The possibility of fully charging a 50 kWh battery of a Nissan Leaf EV is not achievable both in winter and summer
   - The possibility of fully charging a 50 kWh battery of a Nissan Leaf EV is higher in winter than summer
   - The possibility of fully charging a 50 kWh battery of a Nissan Leaf EV is higher in summer than winter