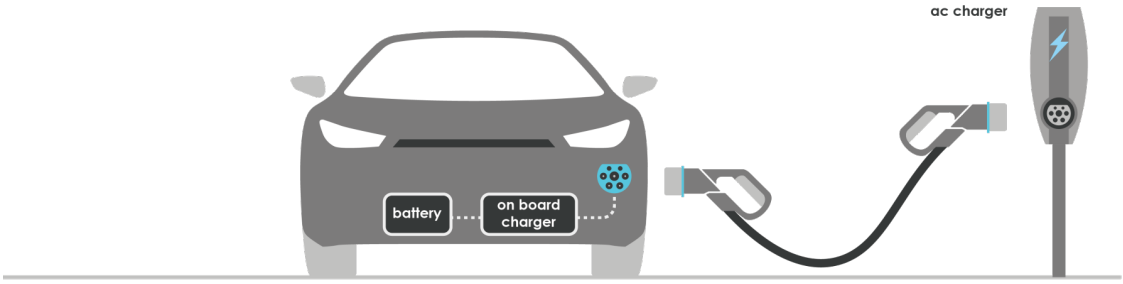
As explained in the lecture, the three common ways to charge an EV are:

1. Conductive charging - AC and DC
2. Inductive charging - Static and Dynamic
3. Battery swap technology

The physical location of the components for converting the power supplied by the grid to that required by vehicle battery can be categorized as onboard and off-board chargers. Onboard chargers are located within the vehicle, and the size and power rating are constrained by the available space within the vehicle. Off-board chargers are located outside the vehicle, and this setup provides more flexibility in terms of the power that can be delivered. Both classes of charging devices must contain control circuits and communicate in real-time with the vehicle battery. This is to ensure that the battery is charged in an optimum way, avoiding any damage to the battery through overcharging. AC charging uses an onboard charger while DC and battery swap use an off-board charger. In case of an inductive charger, a combination of both an onboard and off-board charger are required.

Conductive charging

This is the most common charging method right now and it has 2 categories: AC and DC charging.



Conductive charging - AC

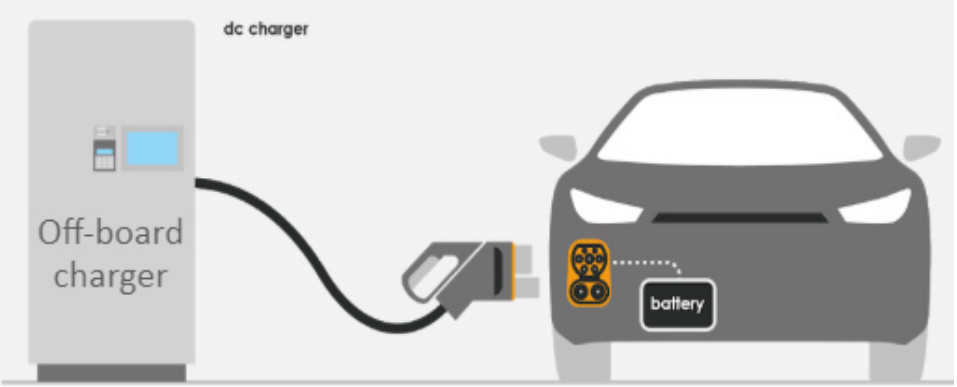
The advantages of this method are:

1. The battery can be recharged anywhere using the AC grid and the onboard EV charger
2. The EV charger can easily communicate with the Battery Management System (BMS) and no additional power electronic converters are needed in the EV charger. This leads to a higher performance and lower cost.

And the disadvantages are:

1. AC power has to be converted into DC power in the car, and there is a limitation of the power output for AC charging due to size and weight restrictions of the onboard charger.
2. AC charging needs relatively long time due to the relatively lower charging power

DC charging is suitable for high power EV charging, and the power output of fast charges is limited only by the ability of the batteries to accept the charging power.



Conductive charging - DC

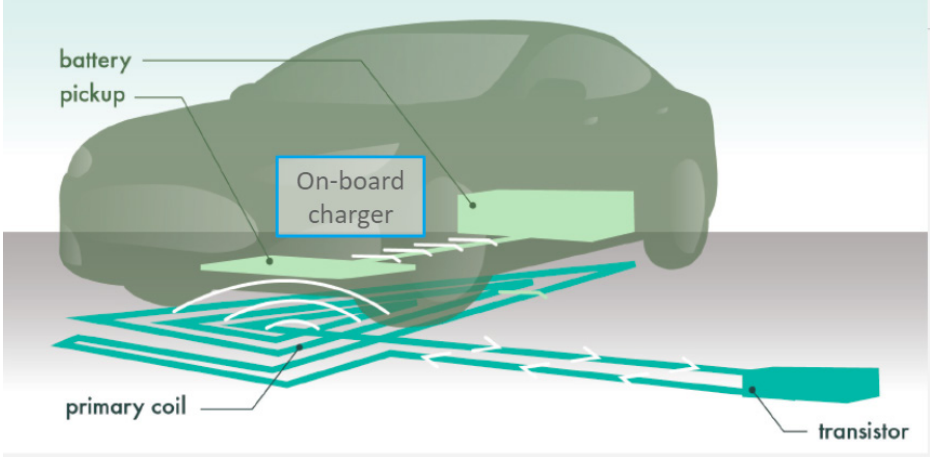
The advantages of this method are:

1. It can be designed with either a high or low charging rate, and is not limited in its weight and size.
2. DC charging with high power requires low charging time.

And the disadvantages are:

1. Higher investment for installation of the charger when compared to AC charging.
2. Adverse impact on power system: high power demand on the grid esp. at peak hours
3. Since the off-board chargers and the BMS are physically separated, reliable communication is important to ensure correct charging conditions.

Inductive charging



Inductive charging - static charging

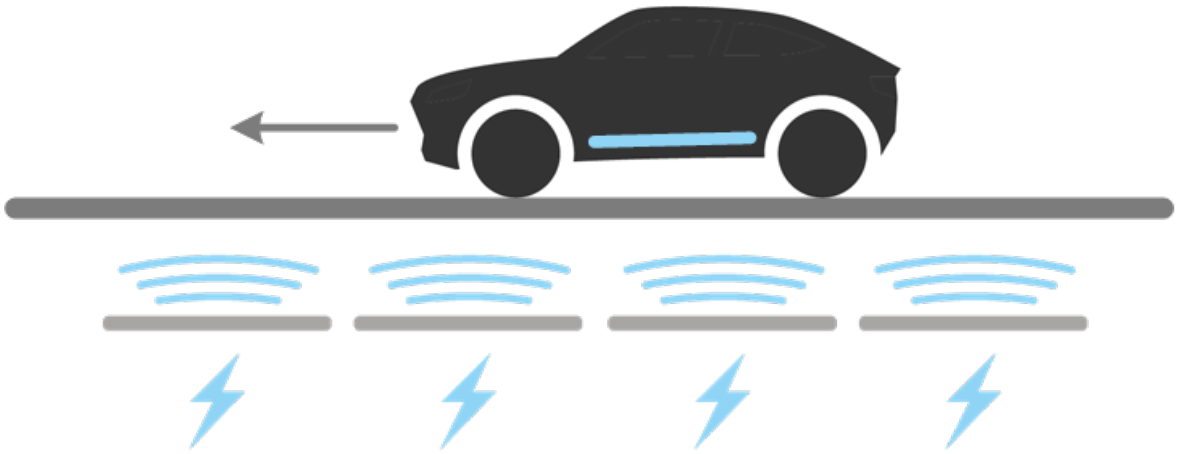
The main idea behind inductive charging is the use of two electromagnetically linked coils. The primary coil is placed on the road surface, in a pad-like construction linked to the electricity network. The secondary coil is placed on the vehicle, ideally on the bottom or top of the car. The 50Hz AC power from the grid is rectified to DC and is then converted to a high-frequency AC power within the off-board charger station. Then this high-frequency power is transferred to the EV side by electromagnetic induction. The coils on the car convert this high-frequency AC power back to DC to charge the EV using the onboard charger.

The advantages of this method are:

1. Convenience
2. Suitable for self-driving cars

And the disadvantages are:

1. High investment
2. Limited space & weight of charge pads
3. Misalignment tolerance between the vehicle and the charge pad
4. Power losses and relatively lower efficiency than conductive charging
5. Electromagnetic radiation exposure



Inductive charging - Dynamic charging

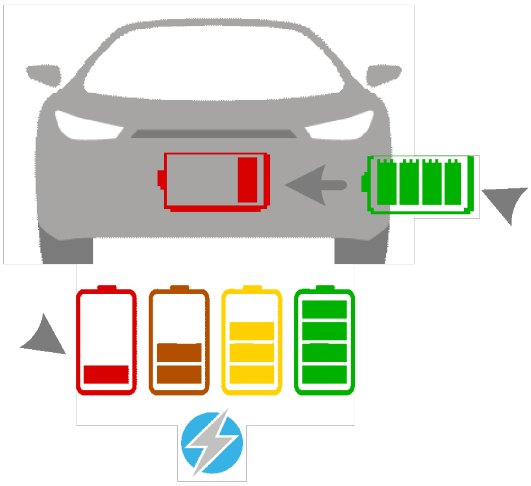
The other way to charge a car wirelessly is called dynamic charging. The coils connected to electric cables which used to provide the power are buried in the road. The coils emit an electromagnetic field that is picked up by vehicles driving over them and converted into electricity to charge the cars. Advantages:

1. Low stand-in charging time
2. Low battery DoD
3. Smaller battery size

So far the dynamic inductive charging is still in the experimental stage because there are many challenges to standardize it. The challenges are:

1. The high cost of investment
2. Foreign objects, coil structure changes and coil misalignment on the road
3. Applicability of different car types and universal coil type selection

Battery swap



The third method of EV charging is battery swap. It 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. The system works on the business concept that the EV user owns the vehicle and not the battery. Battery swap requires a foolproof way to estimate the batteries state of health to check for its usage pattern and to ensure that only authorized vehicles and charging stations can charge it.

The advantages of this method are:

1. No range anxiety
2. Quick and easy refilling like a combustion engine car tank
3. Longer charging times available for the EV battery compared to fast DC charging

The main challenges to this method are:

1. The requirement of standardized battery interface across multiple car manufacturers.
2. Consumer acceptance of not owning a battery and having to change the vehicle battery.

Comparison of EV charging methods

Battery powering methods	Conductive charge		Inductive charge		Battery swap
	AC	DC	Static	Dynamic	
Convenience	☺	☺	☺☺	☺☺☺	☺☺
Cost	€	€€	€€ ~ €€€	€€€€€	€
Service time	Relatively long	Very short	Relatively long	Very flexible	Shortest
Power level	↯↯	↯↯↯↯	↯ ~ ↯↯	↯↯ ~ ↯↯↯	↯ ~ ↯↯↯
Efficiency	▦▦▦▦	▦▦▦	▦▦	▦	▦▦▦▦
Battery lifetime	↻↻↻	↻↻	↻↻↻	↻↻↻↻↻	↻
Impact on grid	■ ~ ■■	■■■■	■■	■■ ~ ■■■	■■■
Standardization challenge	ⓘ	ⓘ	ⓘⓘ	ⓘⓘⓘⓘ	ⓘⓘⓘ

Let's have an overall comparison of all these battery powering methods. From this table, we can see the overall comparison of all battery powering methods.

- It can be observed that the dynamic inductive charging is the most convenient charging method but also the most expensive. Even if the static inductive is cheaper compared to the dynamic one, the average cost of inductive charging is higher than any other method. Dynamic inductive charging has the most flexibility as the car can be charged at any time when on the way and do not need to stop by the service point.
- To power the battery, the battery swap method needs the shortest serving time. For all charging methods except battery swap, the serving time is highly related to the power level. In this case, the DC conductive charging method has the highest power capacity among all the methods.
- There are many factors that impact the efficiency, e.g. the number of power converters and their types, the charging power, and the charging methods. From the table, we can see that, in general, the conductive charging method has higher overall efficiency than inductive charging. It is because the power conversion process using an air gap is less efficient than direct power transfer using cables. Further, the efficiency of inductive charging reduces as a result of the misalignment between the sending and receiving charge pads.
- The battery lifetime is depending on many factors, for example, the charging power (C-rate) and the DOD. The battery lifetime in DC charging has the lowest lifetime because the charging power and hence the corresponding C-rate are the highest. Further, typically at fast charging stations, people want to charge their batteries as much as possible for long distance trips increasing

the depth of discharge as well. In contrary, batteries operated with dynamic inductive charging method has the longest lifetime expectations because the batteries can be charged/discharged with small DOD.

- From the perspective of grid impact, the DC charging method has the most significant impact since it has the highest power level. Besides, the battery swap could also have a high impact on the grid if the charging powers are high as well.
- Finally, considering standardization challenge, the dynamic inductive charging and the battery swap are faced with the most difficult challenges. It is because both methods require standardization between car types, battery size, power level and even shape.