Ch9. Sustainable Energy: Batteries and Electric Vehicles (EVs)

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Chapter outline

1. We start the chapter by watching a video and **discussing** key aspects of the chapter.
2. We study the fundamentals of **voltaic cells** and **lithium-ion batteries**.
3. We study the **EV market evolution**, and the **flexibility potential** in the EV market today, in 2030, and in 2050.
4. We study the **impact of smart charging** on demand and grid structure. We also study the services provided by smart charging EV, and the types of smart charging.
5. We study the **business models** and the **profitability and competitiveness of EV flexibility**.
6. We enumerate the main factors that determine the **cost evolution** and the **implementation of EV**.
7. We compare the advantages and disadvantages of **EV** and **hydrogen vehicles**.
8. We conclude the chapter with a set of **questions** that summarize the main points studied in the chapter.

Discussion

Based on the CNBC video How Tesla, GM And Others Will Fix Electric Vehicle Range Anxiety, discuss the next questions:

1. The video present some of the main trends in EV: sales, number of brands in the market, and number of charge stations? **What do you know about this market**? Evolution of sales, penetration, e-buses, e-tracks?
2. The video explain that the two main challenges for the adoption of EV are infrastructure (charges), and durability of the battery. Can you enumerate **other factors** that could affect the adoption of EV? Batteries costs, variety of models, transport as a service, regulation (ban the sell of non-EV).
3. The video present that there are three main types of chargers level 1 and level 2 (120-240 volts), level 3 (480 volts). Could you explain how the type of chargers could affect the **contribution of EV to the flexibility** of the electricity system?
4. Do you have **any other point** that you consider that it could be relevant for the discussion?

Voltaic cells. Introduction

This section is based on the video Galvanic Cells (Voltaic Cells).

Voltaic cells are devices that use a **chemical reaction to produce electricity**.

As in the chapter where we study hydrogen, the chemical reaction used to produce electricity is the **oxidation-reduction reaction**.

Galvanic cells (voltaic cells) are very popular, since **batteries** work by using the same principle.

The batteries have **chemicals** that react together in an **oxidation-reduction reaction** to produce electricity.

Voltaic cells. Components

1. There are two containers with **water**.
2. One of the containers has a **zinc-sulfate solution** ($ZnSO_4$). The other container has a **copper-sulfate solution** ($CuSO_4$).
3. We have a **piece of zinc metal** in the zinc-sulfate solution ($ZnSO_4$), and a **piece of copper metal** in the copper-sulfate solution ($CuSO_4$).

   In the electrochemical series, there are metals that have a **high tendency to lose electrons** (Li(3.04V), Mg(2.37V), Al(1.66V), Zn(0.76V), Fe(0.44V)); and others metals that have a **high tendency to gain electrons** (Hg(-0,24V), Cu(-0.34V), Ag(-1.69V)).

   The idea behind a battery is to connect metals with tendency to lose electrons with metals with tendency to gain electrons to generate an electric current.
4. A **metal wire** connects the metallic pieces of zinc and copper.
5. Finally, a **salt bridge** connects the two containers with water.

Voltaic cells. Oxidation-reduction

1. **Anode (oxidation process)**. The zinc metal has a high tendency to lose electrons. Therefore, the oxidation process (lose of electrons) will take place in the container where the zinc metal is located.
2. **Cathode (reduction process)**. The copper has a high tendency to gain electrons. Therefore, the reduction process (gain of electrons) will take place in the container where the copper metal is located.
3. **During the oxidation process**, the atoms of zinc (Zn) in the metal lose two electrons. When a metal loses electrons tends to become liquid. Therefore, during the oxidation process **the zinc metal stick becomes more and more thinner**.

   The **half-equation in the anode**:

$$Zn(s) \rightarrow Zn^{+2}(aq) + 2e^{-} \tag{1}$$

Voltaic cells. Oxidation-reduction

4. **During the reduction process**, the atoms of copper (Co^{+2}) dissolved in the copper-sulfate solution ($CuSO_4$) gains two electrons. When a metal becomes neutral, it has a tendency to become solid. Therefore, during the reduction process, **the copper metal stick becomes more and more thick**.

   The **half-equation in the cathode**:

$$Cu^{+2}(aq) + 2e^{-} \rightarrow Cu(s) \tag{2}$$

5. The **balance equation**. By placing together equations 1 and 2, we obtain the balance equation:

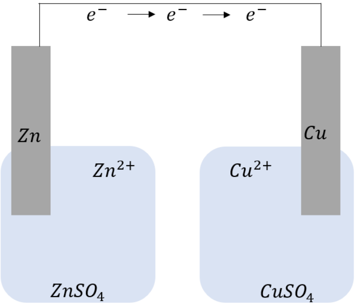
$$Zn(s) + Cu^{+2}(aq) \rightarrow Zn^{+2}(aq) + Cu(s) \tag{3}$$

Voltaic cells. Oxidation-reduction

Balance equation

$$Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$$

Anode:
- **Oxidation** (lose of electrons)
- Zn, high tendency **to lose electrons**



Cathode:
- **Reduction** (gain of electrons)
- Cu, high tendency **to gain electrons**

Oxidation half-equation

$$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$$

Reduction half-equation

$$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$$

Voltaic cells. Salt bridge

1. Due to the loss of electrons, **during the oxidation process**, the zinc-sulfate solution ($ZnSO_4$) becomes more and more positively charged.
2. Due to the gain of electrons, **during the reduction process**, the copper-sulfate solution ($CuSO_4$) becomes more and more negatively charged.
3. Due to the oxidation-reduction reaction, the charge in the containers changes, and that **could stop the flow of electrons**, since the electrons do not want to move to the container full of electrons (electrons repeal each other).

Voltaic cells. Salt bridge

4. To avoid that the flow of electrons stops, a **salt bridge** is used to maintain the charge of the zinc-sulfate ($ZnSO_4$) and the copper-sulfate ($CuSO_4$) solutions neutral.

   The **salt bridge contains** chlorine Cl^- and sodium Na^+.

   The **Chlorine** Cl^- moves to the container where the **oxidation takes place (anode)**, and the **sodium** Na^+ moves to the container where the **reduction takes place (cathode)**.

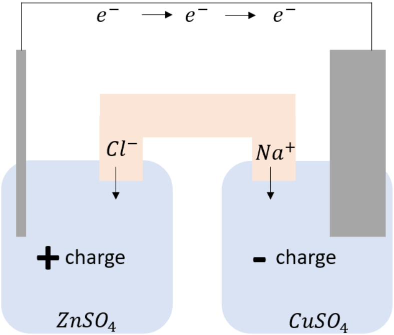
   By doing that, the zinc-sulfate ($ZnSO_4$) and the copper-sulfate ($CuSO_4$) **solutions are balanced** and the flow of electrons can continue.

Voltaic cells. Salt bridge

Salt bridge

Anode:

- **Oxidation** (lose of electrons)
- Zn, high tendency **to lose electrons**



Cathode:

- **Reduction** (gain of electrons)
- Cu, high tendency **to gain electrons**

Lithium-ion battery

This section is based on the next links:

- Lithium-ion battery, How does it work?
- How do Lithium-ion Batteries Work?
- How batteries work - Adam Jacobson
- Lithium-ion battery

As voltaic cells, lithium-ion batteries use a **chemical reaction to produce electricity**.

Lithium-ion battery. Components

1. There are **two electrodes**. The **anode** is a structure that combines carbon and lithium (LiC_6) (lithium-graphite structure). The **cathode** is a structure that combines cobalt and Oxygen (CoO_2) (oxido(oxo)-cobalt).

   The **lithium** has a high tendency to **lose electrons**. The **cobalt combined with the oxygen** has a high tendency to **gain electrons**.

   An electric current is generated by connecting the structure that contains (LiC_6) (anode), and the structure that contains (CoO_2) (cathode).

2. A **metal wire** connects the structures (LiC_6) and (CoO_2).
3. Finally, a **electrolyte** connects the two structures.

   The electrolyte plays a similar role to the **salt bridge** in the voltaic cells, since it leaves to pass lithium-ions (Li^+) to balance the charge in the anode and the cathode to facilitate the flow of electrons.

Lithium-ion battery. Oxidation-reduction

1. **Anode (oxidation process)**. The lithium has a high tendency to lose electrons. Therefore, the oxidation process (lose of electrons) will take place in the anode where the lithium-graphite structure (LiC_6) is located.
2. **Cathode (reduction process)**. The cobalt has a high tendency to gain electrons. Therefore, the reduction process (gain of electrons) will take place in the cathode where the oxido(oxo)-cobalt (CoO_2) structure is located.
3. **During the oxidation process**, the atoms of lithium (Li) in the lithium-graphite structure (LiC_6) lose one electron. When the lithium loses one electron it does not form part any more of the lithium-graphite structure.

   The **half-equation in the anode**:

$$LiC_6 \rightarrow C_6 + Li^+ + e^- \tag{4}$$

Lithium-ion battery. Oxidation-reduction

4. **During the reduction process**, the oxido(oxo)-cobalt (CoO_2) structure gains one electron.

   The **half-equation in the cathode**:

   $$CoO_2 + Li^+ + e^- \rightarrow LiCoO_2 \tag{5}$$

5. The **balance equation**. By placing together equations 4 and 5, we obtain the balance equation:

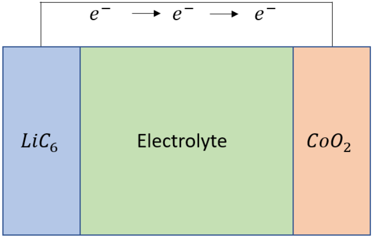
   $$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2 \tag{6}$$

Lithium-ion battery. Oxidation-reduction

Balance equation

$$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2$$

Anode:
- **Oxidation** (lose of electrons)
- Li, high tendency **to lose electrons**



Cathode:
- **Reduction** (gain of electrons)
- Co, high tendency **to gain electrons**

Oxidation half-equation

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

Reduction half-equation

$$CoO_2 + Li^+ + e^- \rightarrow LiCoO_2$$

Lithium-ion battery. "Salt-bridge"

1. Due to the loss of electrons, **during the oxidation process**, lithium-graphite structure (LiC_6) becomes more and more positively charged.
2. Due to the gain of electrons, **during the reduction process**, the oxido(oxo)-cobalt (CoO_2) structure becomes more and more negatively charged.
3. Due to the oxidation-reduction reaction, the charge in the electrodes changes, and that **could stop the flow of electrons**, since the electrons do not want to move to the electrode full of electrons (electrons repeal each other).
4. To avoid that the flow of electrons stops, a **electrolyte ("salt bridge")** is used to maintain the charge of the lithium-graphite (LiC_6) and the oxido(oxo)-cobalt (CoO_2) structures neutral.

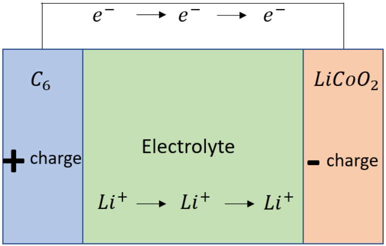
   The electrolyte membrane gives the free Lithium-ions (Li^+) to pass through it and move to the oxido(oxo)-cobalt (CoO_2) structure forming a lithium oxido(oxo)-cobalt ($LiCoO_2$) structure.

Lithium-ion battery. "Salt-bridge"

«Salt bridge»

$$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2$$

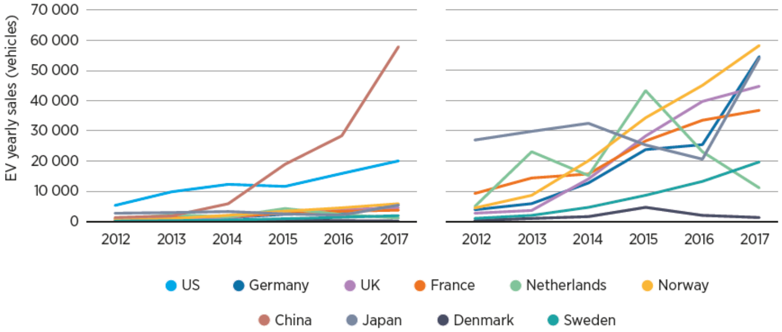
Anode:
- **Oxidation** (lose of electrons)
- Li, high tendency **to lose electrons**



Cathode:
- **Reduction** (gain of electrons)
- Co, high tendency **to gain electrons**

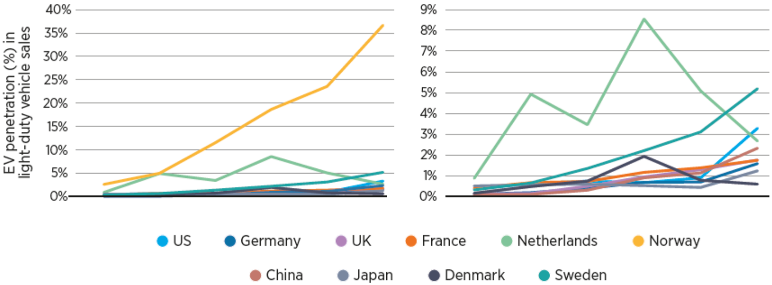
Market evolution

Figure: Evolution EV sales (2012-2017)



Market evolution

Figure: Penetration EV sales (2012-2017)



Market evolution

EV in big companies

The **EV100 initiative**, launched by The Climate Group in 2017, encourages companies to commit to moving towards 100% electric corporate fleets and to install charging infrastructure

E-buses

The market for e-buses is concentrated mainly in **Asia Pacific**, where a market penetration of 27.6% was reached in 2016

In **Europe**, the number of e-buses is expected to grow considerably in the coming years. At least 19 public transport operators and municipalities in 25 European cities have outlined e-bus strategies for 2030

E-tracks.

Although this is still a small market, with less than 10 000 units sold in 2016, the use of electric trucks is expected to rise rapidly in certain sectors such as smaller service and delivery trucks

EV flexibility potential

Cars in general, including EVs, are **parked** for about 95% of their lifetime

Potential to provide a broad range of services to the system. In 2050, around **14 TWh of EV batteries** would be available to provide grid services, compared to **9 TWh of stationary batteries**

Supposing that an EV is connected to charging infrastructure 100% of its parking time, this means that the yearly **"flexibility window" for charging represents about** 85% **of the time**

Incentivising **charging at times when electricity is the cheapest** represents a significant opportunity for the power system and for EV owners

EV flexibility today

1. **Individual electric cars** have predictable charging patterns:
    - **Long-duration (> 4 hours)** charging provides the highest flexibility for the system
    - **Medium-duration (30 minutes to 2 hours)** charging at shopping or leisure centres (movie theatre, gym, etc.) or short-duration (15 minutes to 1 hour) charging provide minimum flexibility for the system and are ill-suited for grid services
2. **Charging patterns of shared and commercial cars** (e.g., taxi and other car fleets) may be less predictable, depending on the business models
3. **Electric bus** charging patterns depend on the place of charging:
    - Long duration (> 4 hours) at the bus depot
    - Medium duration (10 minutes) at the bus end-ofline
    - Very short duration (flash charging) (30 seconds) at the bus stop

EV flexibility in 2030

Increase in flexibility can be expected:

1. **More EVs available to the grid due to falling cost**: EVs get cheaper due to falling battery cost and government policies
2. **Bigger batteries helping to overcome range anxiety**
3. **Cars, charging stations and smart charging and discharging functionalities** become standardised
4. More opportunities for EV drivers to **charge at workplaces**
5. **Fast charging** will remain limited as drivers will use it mainly for long-distance trips and for necessary top-ups given that enough range is available and as long as charging at home remains cheaper

   While higher nominal charging capacity generally increases the challenge of uncontrolled charging, daytime fast charging could be aligned with grid needs in areas with high solar production during the day

EV flexibility in 2050

Mobility business models such as **mobility as- a-service (MaaS)** – i.e., seamless multimodal transport – and technologies such as **autonomous vehicles** may emerge and be broadly implemented, leading to a shift from individual ownership of vehicles to fleet management

Decrease in flexibility can be expected:

1. **Distance travelled by individual cars would increase**, reducing the amount of time that they are idle, connected to the grid
2. MaaS will also eventually impact the number of EVs in the system. The increase in **EV sales would slow down**
3. **Zones of strain on the local power grid can be created once charging is focused in hubs.** These hubs may be relevant for centralised flexibility management in the night but still probably lower than with individual car ownership, as transport service optimisation will aim at maximum usage

Impact of EV on electricity demand

Impact on electricity demand will be limited:

- In a 100% electric mobility scenario for Europe, the energy needs of EVs might represent **no more than** 10% **to** 15% **of total electricity production**. However, EV grid integration might lead to local power issues with increasing EV volumes (Eurelectric, 2015)
- If all 2.7 million cars in Norway were EVs, they would only use $5-6\%$ **of the country's annual hydropower output**
- In a 25% electric mobility scenario for Germany, 10 million EVs by 2035 would translate to an overall consumption increase of only $2.5-3\%$.
- If all light-duty vehicles in the US were electric, they would have represented about 24% of the total electricity demand in the country in 2016.

Impact of EV on electricity demand

The **impact on peak demand**, can be much greater if the additional demand is not distributed smartly. For this, smart charging is key:

- In a 10 million EV scenario for the UK by 2035, **evening peak demand increases by 3 GW if charging is uncontrolled, but increases by only 0.5 GW if charging is smart**
- Modelling of EVs in New England showed that a 25% share of EVs in the system charged in an uncontrolled fashion would **increase peak demand by** 19%, requiring significant investment in grid and generation capacities

  However, by **spreading the load over the evening hours**, the increase in peak demand could be cut to between 0% and 6%. And charging only at off-peak hours could avoid any increase at all in peak demand

Impact of EV on electricity demand

The **impact on local distribution grids** might be significant if not managed with smart charging:

- Xcel Energy, Colorado in the US demonstrated that 4% of distribution transformers could be overloaded at EV market penetration of 5% if charging is aligned with peak load times.
- The My Electric Avenue Project in the UK identified a need for 32% of distribution circuit upgrades with a $40 - 70\%$ share of electrified cars.

Impact on grid infrastructure

Fast charging represents a challenge for grid infrastructure development. The higher the power, the more capacity you need from the distribution grid

In addition, the locally deployed charging station/cables and vehicle must support this power. Both of those are technologically feasible but come at a price:

1. Vehicles require **more expensive electronics** and protection devices.
2. Grid connection of fast-charging stations requires **bigger cables and transformers**.
3. Such charging stations require more expensive electronics and cooling as well as protecting devices.
4. **Active cooling of the charging cable is needed if very heavy cables are to be avoided**. Increasing voltage from today's level will mitigate the need for heavier cable and/or active cooling, but this is not an optimal solution considering the interoperability with the existing infrastructure (and with the existing EVs).

Impact on grid infrastructure

EV charging impact on Hamburg's distribution grid.

Hamburg is currently the city with the highest number of charging points in Germany (several hundred charging points in households and 810 public charging points as of November 2018). The city expected to install 1 000 public charging points by the beginning of 2019. Electrification of public buses and EV growth are the most critical drivers of load development in the city. The majority of EVs will be in the suburbs where, in Hamburg's case, the grid is weaker.

The local distribution system operator, Stromnetz Hamburg, ran a load development analysis to identify critical situations for uncontrolled charging of EVs with charging point loads of 11 kW and 22 kW. **A** 9% **EV share, corresponding to 60 000 EVs loading in private infrastructure, will cause bottlenecks in** 15% **of the feeders in the city's distribution network**

Services provided by smartly charged EVs

Adjusting charging patterns that today stand idle in parking for most of the time (90 – 95% of the time for most cars) could **contribute to**:

1. **Peak shaving (system level/wholesale)**: flattening the peak demand and filling the "valley" of demand by incentivising late morning/ afternoon charging in systems with large penetration of solar and nighttime charging that could be adjusted following nighttime wind production as cars are parked for longer time than they need to fully charge
2. **Ancillary services (system and local levels / transmission and distribution system operators)**: supporting real-time balancing of grids by adjusting the EV charging levels to maintain steady voltage and frequency
3. **Behind-the-meter optimisation and "back-up power" (local level / consumers and prosumers)**: this includes increasing self-consumption of locally produced renewable electricity as well as lowering dependence on the electricity grid

Types of smart charging

1. Basic switching on and off of the charging or unidirectional control of vehicles (**V1G**) that allows for an increase or decrease in the rate of charging

2. For **V2X**, two specific configurations are particularly relevant:

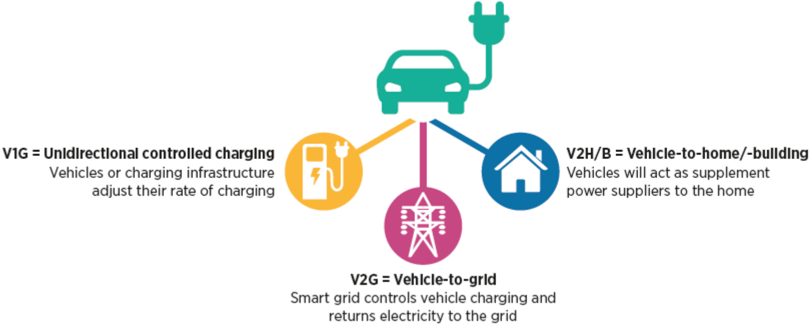
- **Vehicle-to-home (V2H)** or **vehicle-to-building (V2B)** do not typically directly affect grid performance

  The EV is used as a residential back-up power supply during periods of power outage or for increasing self consumption of energy produced on-site (demand charge avoidance)

- **Vehicle-to-grid (V2G)** refers to providing services to the grid in the discharge mode

  The utility / transmission system operator may be willing to purchase energy from customers during periods of peak demand, and/or to use the EV battery capacity for providing ancillary services, such as balancing and frequency control, including primary frequency regulation and secondary reserve

Types of smart charging



Profitability and competitiveness of EV flexibility

1. **Price spreads** in the system may be lowered – for example, by daytime solar PV generation – and may not rise again if there is sufficient flexibility in the system (low price spreads are expected in the German and Spanish day-ahead markets)
2. **Revenues from ancillary services** may not provide sufficient flexibility in all markets
3. **EVs will compete with other types of decentralised flexibility such as demand-response resources**, and with the used EV batteries themselves. Second-life EV batteries will be inexpensive and are already being deployed by automakers today.

Types of EV flexibility

1. **Unidirectional V1G** could be handled by a charging point manager. If it were performed remotely, this could be done via a **software-as-a-service (SaaS) structure**, which could manage numerous charging points and other loads on a site
2. **V2G and second-life batteries** operation **require an aggregator**. Tailor-made combining of smart energy services / home and building energy management (smart charging, V2X) with V2G as part of a larger portfolio of aggregated distributed energy resources as well as second-life batteries will be commonplace
3. **Virtual Power Plant** operator

   Depending on the charging preference, each EV can provide either positive or negative control reserves

   The Virtual Power Plant operator will be able to combine user preferences, car data, and charging station information to provide a continuous forecast of the available capacity

Types of EV flexibility

4. The current **Vehicle-grid integration (VGI)** is based largely on the provision of charging management software from developers of proprietary solutions to utilities and fleets

   The case studies of **Enel and Nissan** (green box below) illustrate this emerging business strategy from the utility and the Original equipment manufacturer (OEM) perspectives, respectively

5. Energy services platforms also may be integrated into other platforms and by other actors from other sub-sectors. For example, **smart building "as-a-service"** integrating energy management is gaining traction, and collecting data from occupants, aggregation and Vehicle-grid integration (VGI) back to the grid could be the next step, even if not the current focus

   This space is currently dominated by electronics giants (Schneider Electric, Siemens, Panasonic).

Types of EV flexibility

Future energy services platform providers: Enel and Nissan strategies

EV clients received compensation in the form of a reduction in their electricity bill in exchange for provision of grid services

Enel integrated the purchased V2G power into its **larger aggregated ancillary services portfolio**, thus creating a “buffer” for uncertainties due to possible deviations in the schedules of individual vehicles, without directly controlling them

The automaker **Nissan** also eyes valorisation of aggregated flexibility as an additional revenue stream

In January 2018 Nissan launched a new solar generation and energy storage system for domestic use in the UK (Nissan, 2018). That solution will allow UK homeowners to **increase the rate of self-consumption** from on-site PV and cut energy bills by up to 66%

Cost and competitiveness of EVs

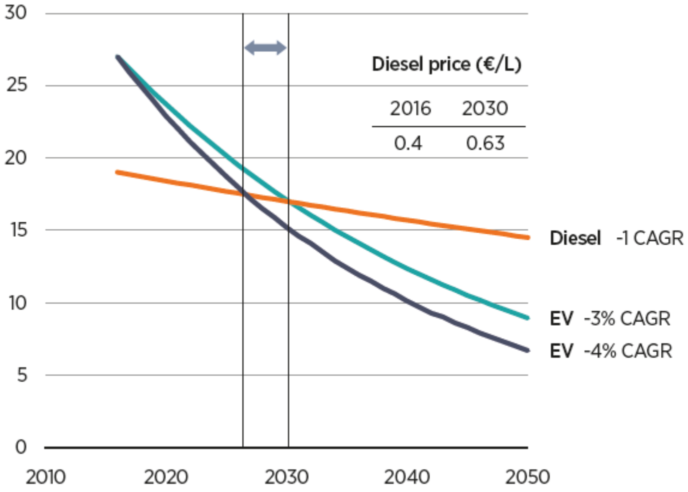
1. Until now, the most crucial factor that has led to a substantial cost decrease for EVs in the last few years is the **decline in battery pack costs**

2. Another notable factor that has helped to reduce EV prices over the years is the increasing **variety of models** being offered in the market

3. **New mobility business models** oriented to car-sharing practices that are expected by 2050, there will be a shift from privately owned cars to shared vehicles

4. Setting **bans on fossil fuel vehicle sales** by as early as 2025 (in the Netherlands) or by 2030 to 2040 (in France and the UK)

Cost and competitiveness of EVs



Shared e-mobility: Mobility-as-a-service

Changing mobility needs will lead to the rise of business models that could transform mobility systems over the coming decades

Removing the pain points that travellers face during their journeys could prove to be a crucial opportunity for new businesses to appeal to customers

A new concept is already paving the way for these business opportunities to emerge, via a shift from an ownership-centred approach of transport to mobility options that are consumed as a service

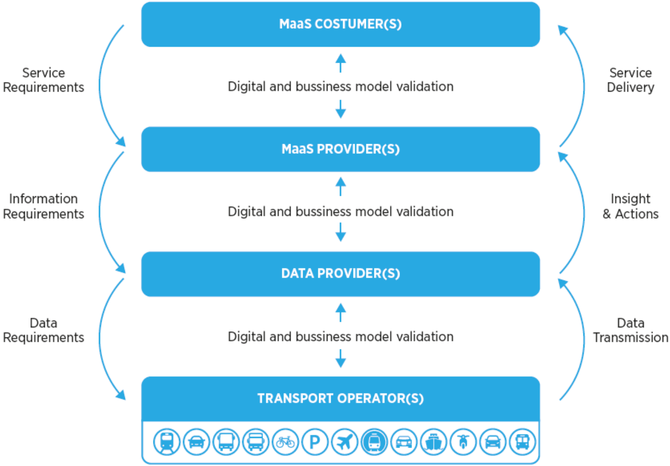
This service-centred mobility is called **mobility as-a-service (MaaS)**.

A MaaS offering thus consists of **four complementary functionalities**: **trip planning**, **booking**, **payment** and **ticketing/billing**

The MaaS design requires **four main actors**: The **customers**, the **MaaS providers**, the **data providers** and the **transport operators** (figure below)

Shared e-mobility: Mobility-as-a-service

Figure: Simplified mobility-as-a-service value chain



Hydrogen vs. batteries

Hydrogen vs. batteries

Questions to summarize the chapter

1. Can you describe briefly the **state of the play in the EV sector**? Market evolution, market penetration, EV in big companies, e-buses, e-tracks?
2. Can you identify the main sources of **EV flexibility potential** today, in 2030, in 2050?
3. Which will be the **impact of smart charging** on electricity demand, electricity peak demand, grid infrastructure?
4. Which will be the **services provided by introducing smart charging EV**? Peak shading, ancillary services, back-up power.
5. Can you describe the **main smart charging methods**? V1G (grid), V2B (building), V2G (grid).
6. Can you enumerate the main factors that determine the **cost evolution** and the **implementation of EV**? Battery cost, variety of models, business models (mobility as a service), regulation.
7. Can you explain the main actors that determine the **e-mobility business model**? **customers**, the **MaaS providers**, the **data providers** and the **transport operators**