ENE425 Sustainable Energy and App Development

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March 11, 2022

Contents

Chapter 9

Sustainable energy. Batteries and electric vehicles

In this chapter we study the relation between batteries, electric vehicles and the electric system.

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.

9.1 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?

9.2 How do batteries work?

We study first how do galvanic cells (voltaic cells) work, and based on that the lessons learned in that section, we study how do lithium-ion batteries work.

9.2.1 How do galvanic cells (voltaic cells) work?

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

Galvanic cells also called 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.

Before to explain the chemical reaction that generates electricity, we introduce the **parts of a voltaic cell** (figure 9.1).

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.

We explain how voltaic cells work. We divide the entire process in two steps. First, we explain the **oxidation-reduction process**. Second, we explain the role of **salt bridge** in the entire process. By splitting the process in two parts, we will make easier to understand the entire process. Moreover, this will also help us to know how do lithium-ion batteries work (next section).

Oxidation-reduction reaction (figure 9.1).

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**:

$$Zn(s) \rightarrow Zn^{+2}(aq) + 2e^{-} \tag{9.1}$$

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**:

$$Cu^{+2}(aq) + 2e^{-} \rightarrow Cu(s) \tag{9.2}$$

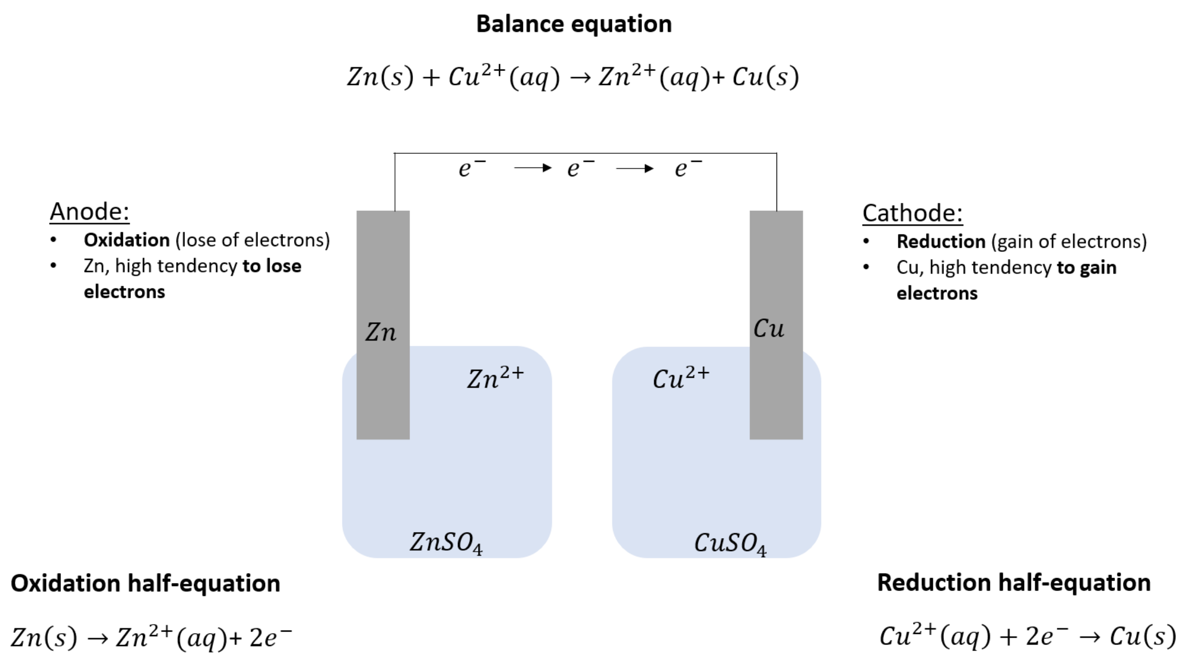
5. The **balance equation**. By placing together equations 9.1 and 9.2, we obtain the balance equation:

$$Zn(s) + Cu^{+2}(aq) \rightarrow Zn^{+2}(aq) + Cu(s) \tag{9.3}$$

Salt bride (figure 9.2).

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).

Figure 9.1: Voltaic cell (oxidation-reduction process)



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^- move 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.

9.2.2 How do lithium-ion batteries work?

This section is based on the next links:

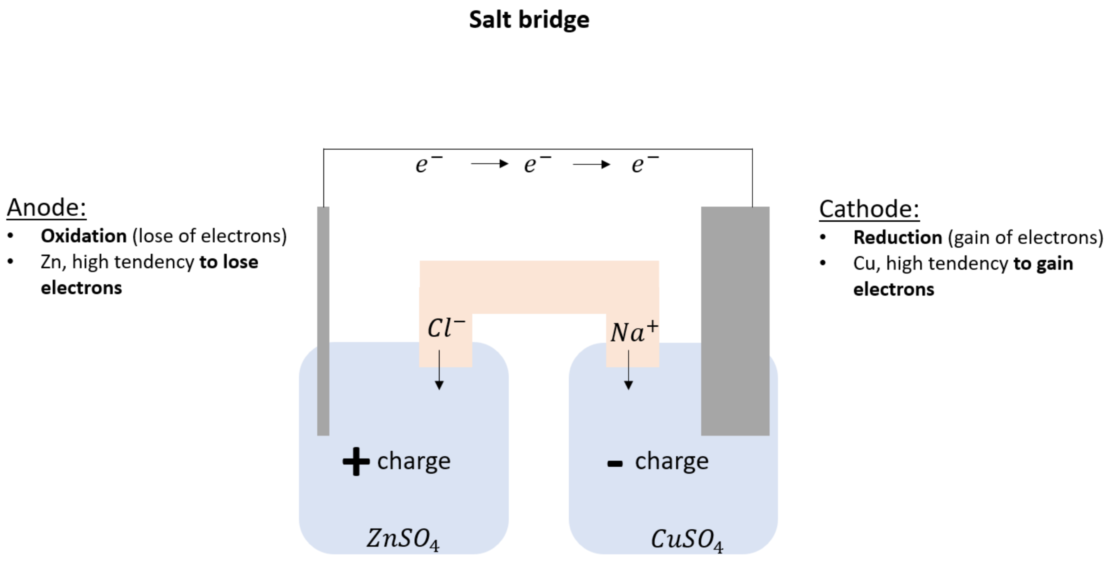
- Lithium-ion battery, How does it work?
- How do Lithium-ion Batteries Work?
- How batteries work - Adam Jacobson
- Lithium-ion battery

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

Before to explain the chemical reaction that generates electricity, we introduce the **parts of a voltaic cell** (figure 9.3).

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).

Figure 9.2: Voltaic cell. Salt bridge



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.

We explain how voltaic cells work. We divide the entire process in two steps. First, we explain the **oxidation-reduction process**. Second, we explain the role of **electrolyte** in the entire process.

<u>Oxidation-reduction reaction (figure 9.1).</u>

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.

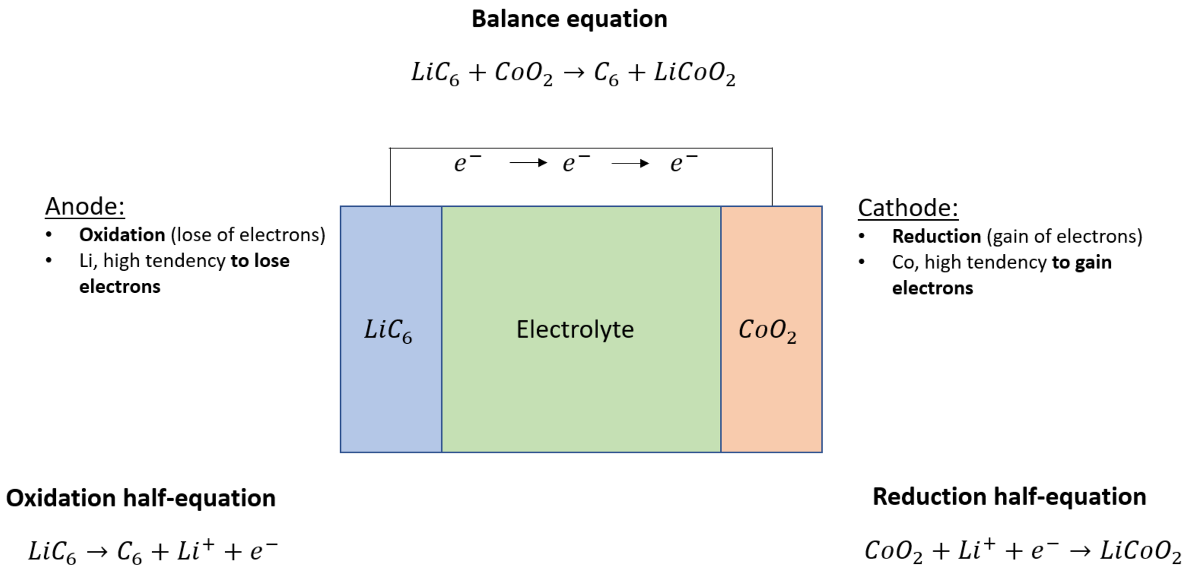
2. **Cathode (reduction process)**. The cobalt has a high tendency to gain electrons. Therefore, the reduction process (gain of electrons) will take place in the cathode where the oxido(oxo)-cobalt (CoO_2) structure is located.

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**:

$$LiC_6 \rightarrow C_6 + Li^+ + e^- \tag{9.4}$$

Figure 9.3: Lithium-ion battery (oxidation-reduction process)



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

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

$$CoO_2 + Li^+ + e^- \rightarrow LiCoO_2 \tag{9.5}$$

5. The **balance equation**. By placing together equations 9.4 and 9.5, we obtain the balance equation:

$$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2 \tag{9.6}$$

Electrolyte ("Salt bride") (figure 9.2).

1. Due to the loss of electrons, **during the oxidation process**, lithium-graphite structure (LiC_6) becomes more and more positively charged.

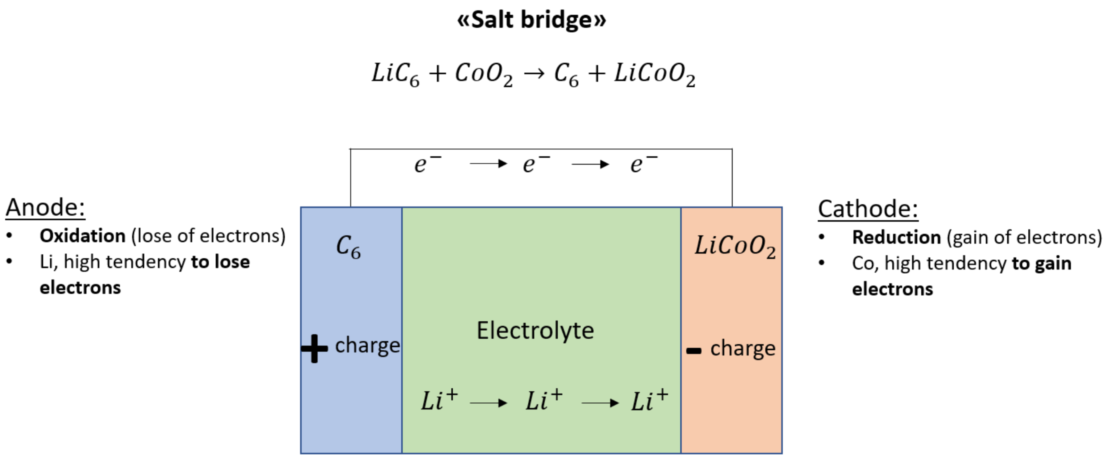
2. Due to the gain of electrons, **during the reduction process**, the oxido(oxo)-cobalt (CoO_2) structure becomes more and more negatively charged.

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.

Figure 9.4: Lithium-ion battery. Electrolyte ("Salt bridge")



When an electric current is connected to the battery, the process is reversed, and the lithium passed through the electrolyte membrane to form again the lithium-graphite structure (LiC_6) in the anode. During the charging-discharging process some permanent crystals are formed and that makes more difficult the flow of electrons. In the long-term those permanent crystals the battery stop working.

9.3 State of play

9.3.1 Market evolution

EV sales evolution.

According to the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), 5.6 million EVs were on the world's roads at the beginning of 2019. **China and the United States (US)** are the largest markets, with 2.6 million and 1.1 million EVs, respectively. On average, EV sales grew rapidly during the period 2012 to 2017, with a **compound annual growth rate (CAGR) of** 57%. However, the market is still in an incipient phase, with EVs representing only 1.3% of all light-duty vehicles sold in 2017.

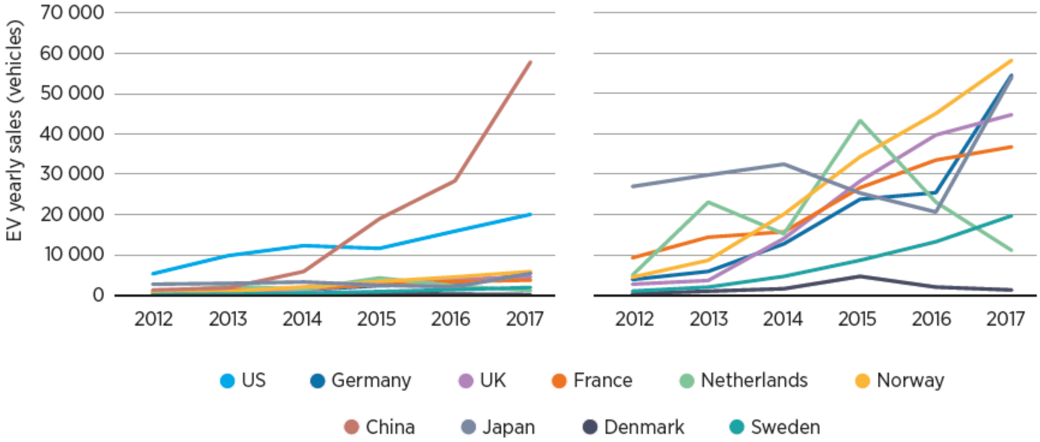
The **Chinese** EV market has experienced the largest increase in sales, with a CAGR of 114% between 2012 and 2017. In 2015 China surpassed the US in total EV sales, and in 2017 it was responsible for 48% of worldwide electric light-duty vehicle sales. The Chinese government has offered direct monetary incentives to support the purchase of EVs, including one-time subsidies and purchase tax exemptions, as well as non-monetary incentives, such as restrictions on registrations for ICE vehicles.

After China and the US, the next largest markets are in **Europe**, with considerable growth in EV sales from 2012 to 2017 in Germany (CAGR of 75%), Norway (70%) and the UK (68%). Figure 9.5 shows the evolution of EV sales in the 10 countries that represented 88% of worldwide electric light-duty vehicle sales in 2017.

EV penetration.

Although the Chinese and US markets are the largest for EV sales, other countries have had greater success in integrating EVs into their overall vehicle fleets. Figure 9.6 shows the evolu-

Figure 9.5: Evolution EV sales (2012-2017)



Source: IRENA (2019a)

tion of market **penetration of EVs** in light-duty vehicle sales. **Norway** has made remarkable progress since 2012, becoming a global leader with an almost 40% share of EVs in 2017. This was the result of a favourable policy environment in recent years comprising a large range of incentives, from tax breaks and exemptions to waivers on road tolls and ferry fees.

After Norway, the markets with the highest progress in EV integration between 2012 and 2017 were **Sweden**, the **US** and the **Netherlands**, with EV shares representing 5.1%, 3.3% and 2.7%, respectively, of the light-duty vehicle market in 2017. The remaining six largest markets did not exceed ratios of 2.5% of EV penetration and rank similarly to the global average.

EV in big companies.

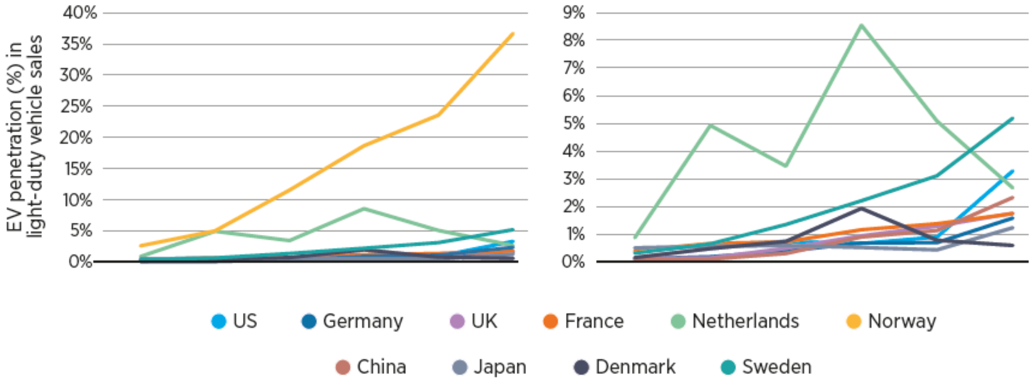
The **EV100 initiative**, launched by The Climate Group in 2017, encourages companies to commit to moving towards 100% electric corporate fleets and to install charging infrastructure. In its first several months, the initiative had already signed on **10 multinationals**, among them the Swedish power company Vattenfall, IKEA Group and the Chinese Internet giant Baidu (The Climate Group, 2017). **Vattenfall** has the most timeambitious goal of the initiative so far, with the company setting targets to shift its fleets (3 500 light-duty vehicles) to 100% electric by 2022 as part of its goal to be climate neutral by 2050. The replacement will take five years and will include fleets in Germany, the Netherlands and Sweden.

The **French postal service** La Poste is also a pioneer in the field, owning 35 000 EVs out of a total fleet of 75 000 vehicles. In 2017 **Germany's Deutsche Post DHL Group** also set a target to achieve zero-emission logistics by 2050, in part through the use of EVs.

E-buses.

The market for e-buses is concentrated mainly in **Asia Pacific**, where a market penetration of 27.6% was reached in 2016. Since 2014 there has been a large uptake of e-buses in **China**, which is now responsible for 99% of the worldwide sales and fleet. Market penetration in **North America and Western Europe** is around 0.6%. Whereas China reached 340 000 e-buses in 2017, the largest fleet of e-buses in Europe is in the UK and accounts for only 344 units.

Figure 9.6: Penetration EV sales (2012-2017)



Source: IRENA (2019a)

China is at the leading edge of the electrification of public transport buses because of the air pollution problems in its cities and industrial zones. The strategy of electrifying public transport comes from city administrations that want to reduce air pollution. The rapid and strong uptake of e-buses in Shenzen, for example, has helped to dramatically reduce the city's greenhouse gas emissions. The shift to e-buses is also supported by the national government, which has huge ambitions in mass transit. Apart from electrification, China has invested in a national high-speed railway network, subways and bus rapid transit.

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 2020.

E-tracks.

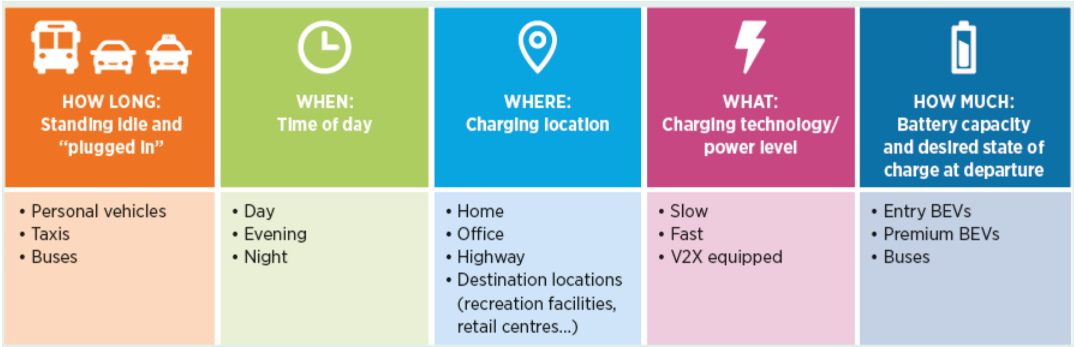
The largest market for electric drive trucks is in **Asia Pacific**, responsible for around half of worldwide sales in 2016. However, electric trucks reached the highest market penetration in **Western Europe**. Although this is still a small market, with less than 10 000 units sold in 2016, the use of electric trucks is expected to rise rapidly in certain sectors such as smaller service and delivery trucks (IRENA, 2017a).

9.3.2 EV flexibility potential

The uptake of smart charging for electric mobility is expected to establish a positive feedback loop with the integration of renewables, given that e-mobility is a power-dense, mobile and controllable load. Studies have shown that **cars in general, including EVs, are parked for about** 95% **of their lifetime**. This, combined with their storage capacity, could make **EVs an attractive flexibility solution to support system operation**. They can become grid-connected storage units with a 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 (IRENA, 2019b).

The typical electricity consumption of an EV driving 15 000 km/year is about 3 000 kWh/year. Even with slow charging (i.e., charging with low power, say 3.7 kW), the total time needed to charge the yearly energy is about 10% of the time the car stands idle. Supposing that an EV is connected to charging infrastructure 100% of its parking time, this means that the yearly

Figure 9.7: Factors determining the amount of available flexibility from a single EV



Source: IRENA (2019a)

"flexibility window" for charging represents about 85% **of the time**. Theoretically, this would translate into a flexible energy output of about 3 000 kWh/year per car. In other words, EVs can be charged in a fraction of their parking time. Incentivising charging at times when electricity is the cheapest represents a significant opportunity for the power system and for EV owners.

In practice, flexibility can be lower due to drivers' time constraints, with fast charging, or when the vehicle is parked but not plugged in. The different factors that determine the amount of available flexible (dis-) charging energy from EVs available in the system are summarised in figure 9.7.

EVs providing power system flexibility today

Today, the EV fleet is very limited and the cars still have relatively small batteries. EVs can already help maximise self-consumption of on-site renewable production. However, the flexibility that EVs provide to the grid is limited. Their aggregated storage capacity today is marginal from a power system perspective.

How long the car can be connected to the grid depends on the immobilisation time, which is determined by the type of vehicle and its use. Taxis or buses that travel a high daily distance will have less immobilisation time and therefore less flexibility than single cars used by individuals. While an **electric bus or truck** may use 100% or more of battery capacity every day, **passenger cars and two-wheelers** may use 40% to 50% of it.

<u>When and where.</u>

When and where the vehicle is charged also depends on the car type, its use, the **geography** and the **availability of the infrastructure**:

1. **Individual electric cars** have predictable charging patterns:
    - **Long-duration (> 4 hours)** charging provides the highest flexibility for the system: most of the charging takes place at home during the evening, and at night and at the workplace during the day. EV drivers without home charging need assigned workplace charging.
    - **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: fast charging on highways is rather exceptional today as EVs are mostly not yet used for long trips (due mainly to the limited range issue and the lack of appropriate charging infrastructure).

2. **Charging patterns of shared and commercial cars** (e.g., taxi and other car fleets) may be less predictable, depending on the business models. Nevertheless, the transport service revenue is critical and the time of standing still should be reduced to a minimum, leading to smaller time with grid connection and higher charging power, compared to individual cars.

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.

Depending on the **geography** and specifically the access to a **private parking space at the residential level**, the proportions among the charging locations might differ. In less densely populated areas, most of the charging cycles are performed at home or at work. In densely populated cities with no charging points at home or at work, a larger proportion of the charging could be done in public places in the city. Large parking spaces or bus depots have more technical opportunities and incentives to contribute to energy flexibility than do disperse charging locations.

EVs providing power system flexibility by 2030

By 2030 individual ownership of vehicles will most likely still prevail over car sharing. As a result, an **increase in flexibility** can be expected:

- **More EVs available to the grid due to falling cost**: EVs get cheaper due to falling battery cost and government policies, as outlined in the previous section.

- **Bigger batteries helping to overcome range anxiety**: there will be more EVs with larger batteries connected to the grid. Battery packs will be bigger – increasing from 20-30 kWh currently to 40-60 kWh, with ranges of around 300 km becoming widespread in the next two years and growing even further.

- **Cars, charging stations and smart charging and discharging functionalities**: as standardisation progresses and as the requirements for better control of the charging power increase, the vehicles and charging points will have smart charging options including discharging as a common feature (provided by auto manufacturers), and technically enabling provision of ancillary services to the grid.

- More opportunities for EV drivers to **charge at workplaces**.

- **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.

EVs providing power system flexibility by 2050

Between 2030 and 2050, this picture could **change substantially**. Mobility business models such as **mobilityas- 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.

Studies have shown that "ride-sharing" could lead to an **increase in the number of kilometres** driven as the shift from public transport towards shared private transport occurs at a larger scale. However, it also should lead to lower use of private cars with low passenger occupancy, which could in turn imply a reduction in the net emissions of the transport system.

Nevertheless, downwards pressure on available flexibility is likely to occur under this scenario, as:

- **Distance travelled by individual cars would increase**, reducing the amount of time that they are idle, connected to the grid.
- MaaS will also eventually impact the number of EVs in the system. The increase in **EV sales would slow down**: under the assumption that the EV revolution will precede the advent of an advanced MaaS ecosystem, new business models in MaaS will translate to downwards pressure on car sales for individuals after approximately 2030, following years of increasing market growth.
- **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. Vehicle fleets will have to be steered towards an optimised fleet charging and routing, contributing to the goals of EV grid integration and optimised renewable energy use.

9.4 Smart charging

9.4.1 Impact on electricity capacity and demand

If EVs were charged simultaneously in an uncontrolled way they could increase the peak demand on the grid, contributing to overloading and the need for upgrades at the distribution level. The extra load may even result in the need for upgrades in the generation capacity (or at least in an altered production cost profile). The extent of possible impacts would depend on the power system's electricity mix, grid typology and penetration of EVs, as demonstrated by various trials and studies conducted globally.

The studies converge on **three main conclusions** about the **impacts of EVs on the power system** and how these impacts can be mitigated:

1. **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.

2. The **impact on peak demand**, however, 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. With smart EV charging, the lowest price periods could see demand increase by 7 GW.
   - 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.
3. The **impact on local distribution grids** might also 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.

9.4.2 Impact on grid infrastructure

EV charging will have an impact on **distribution grid investments**. The scope of grid investments (in terms of cables and transformers) that will need to be made in a given location will depend at least on the following parameters:

1. **Congestion:** such as in the local distribution network prior to any EV deployment.
2. **Simultaneity factor:** as applied based on the size of each distribution grid. The simultaneity factor/coefficient measures the probability that a particular piece of equipment will need to be switched on at the same time as another piece of equipment. Every distribution system operator considers a different simultaneity factor.
3. **Load characteristics:** for example, the impact of uncontrolled EV charging will be higher in locations with high shares of electric heating (thus leading to higher grid reinforcement). But if smart charging is used in such locations, it may be included with lower grid reinforcements than in locations where no electric heating is used, as the local grids are dimensioned for higher peaks.
4. **Generation assets connected at low voltage level:** for example, integration of high shares of solar PV connected at low voltage level (e.g., in Germany) could be facilitated with smart charging, whereas in locations with no or very low shares of solar PV, EVs could increase the strain on local grids.
5. **Grid code limits and other regulations:** for example, national grid codes define physical constraints in terms of both voltage and frequency variations that distribution system operators have to respect, and investment in grid reinforcement if these country-specific limits are exceeded due to EV charging.

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).

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.

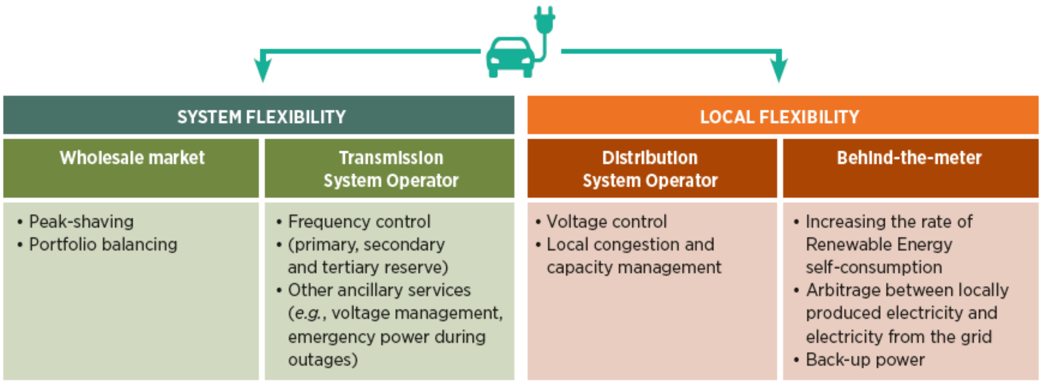
The local distribution system operator, Stromnetz Hamburg, ran a load development analysis to identify critical situations for uncontrolled charging of EVs with charging point loads of 11 kW and 22 kW. **A 9% EV share, corresponding to 60 000 EVs loading in private infrastructure, will cause bottlenecks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

To avoid these critical situations, Stromnetz Hamburg assessed that investment needs for reinforcing the local grids would reach at least EUR 20 million. Stromnetz Hamburg is also exploring alternative solutions to address the problem. The key is to decrease the simultaneity, meaning decreasing the number of EVs that are charged at the same time on the same local grid. For that, a smart solution using digital technologies is being tested, which includes a real-time communication system that enables the distribution system operator to reduce the load of the charging points needed to address the problem. The 11 kW charging points, for example, can reduce their load from 16 amperes (A) to 8 A, allowing EVs to be charged but in a longer period of time.

9.4.3 Services provided by smartly charged EVs

Smart charging using vehicle-grid integration (VGI) technologies is a means of managing EV loads. This is done either by customers responding to price signals, by the Electric vehicle supply equipment (EVSE) automated response to control signals that react to the grid and market situations, or by a combination of the two while respecting customers' needs for vehicle availability. It consists of shifting some charging cycles in time or modulating the power in function of constraints (e.g., connection capacity, user needs, real-time local energy production). Smart charging therefore is a way of optimising the charging process according to distribution grid constraints and local renewable energy availability, as well as the preferences of drivers and EVSE site hosts.

Figure 9.8: Potential range of flexibility services by EVs



Source: IRENA (2019a)

If charged smartly, EVs can not only avoid adding stress to the local grid but also provide services to fill flexibility gaps both on the local level and on the system level (figure 9.8).

The EVs can operate as grid-connected storage units with a potential to provide a broad range of services to the system. They could alternate their charging patterns to flatten peak demand, fill load valleys and support real-time balancing of grids by adjusting their charging levels.

Smart charging not only mitigates EV-caused demand peaks but also flattens the load curve to better integrate VRE, both at the system level and locally, at the shorter term time scales. More specifically, 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. Early-evening charging that may otherwise increase peak demand would be deferred in this way.

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 and reducing the energy bill by buying cheap electricity from the grid at off-peak hours and using it to supply home when the electricity tariff is higher (during evenings).

Key technical terms for classifying battery technologies:

- **End of life (EoL)**: moment when the battery retains only a fraction (typically 70initial capacity. It is expressed as a percentage of initial capacity.
- **Depth of discharge (DoD)**: the percentage (compared to full capacity) to which the battery can be discharged.
- **State of charge (SoC)**: the capacity of the battery expressed as a percentage of the full capacity at which the battery is during usage charge.
- **Cycling rate (C-rate)**: the rate of charge or discharge. 1C refers to a charge or discharge in 1 hour, 2C refers to 2 hours, and 0.5C refers to 30 minutes.

9.4.4 Types of smart charging and their implementation

Smart charging includes different pricing and technical charging options. The basic technical options are summarised in figure 9.9.

Direct control mechanisms enabled by the EV and the charging point will be necessary as a long-term solution at higher penetration levels and for delivery of close-to-real-time balancing and ancillary services. Such mechanisms range from basic switching on and off of the charging or unidirectional control of vehicles or EVSE (**also called V1G**) that allows for an increase or decrease in the rate of charging, to more challenging bidirectional **vehicle-to-everything (V2X)**.

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.

In the **V1G**, the driver, the EV charging site host or the aggregator can be rewarded only for adjusting their rate of charging up and down compared to the initial charging power (3 kW is assumed for illustration). In **V2G**, EVs can charge and discharge electricity from and to the grid, respectively. The size of the "bids" for grid services corresponds to the capabilities of the EV and the requirements in the given market.

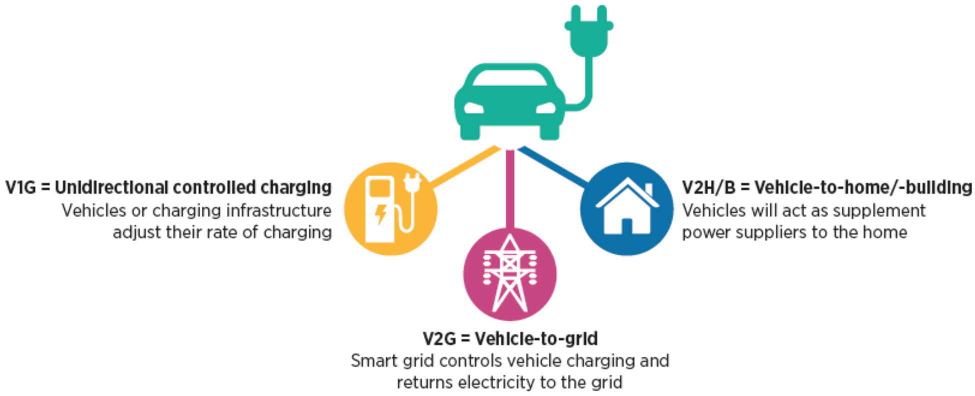
9.5 Business models

9.5.1 E-mobility market actors

The e-mobility market includes the **following segments**:

- **EV sales**: while most light-duty vehicles are sold via leasing, public procurement needs to be considered for public transport means such as buses.
- **Mobility services**: these services include e-car sharing, intermodal transport, fleet management, electromobility service provision and, increasingly, collection and analytics of data from drivers, fleet managers and charging stations.

Figure 9.9: Forms of smart charging



Source: IRENA (2019a)

- **Electricity sales to power EVs**: this includes electricity retail sales as well as re-selling by charging infrastructure providers.
- Installation and maintenance of charging infrastructure.
- **Charging station operations** (smart charging / data management / billing).
- E-roaming: this is key for interoperability of charging services as well as regional/national charging independence.
- **Advanced grid services** such as aggregation and V2G (emerging).

Many traditional as well as new actors from both the mobility and energy sectors are active in this emerging market. In addition to Tesla – with its vision of an integrated mobility company stirring change in the sector – new independent providers include **e-car-sharing service providers** (e.g., Zen Car and BlueIndy by Bolloré), dedicated charging **station developers**, **operators**, **data managers**, **e-roaming platform providers**, as well as providers and aggregators of advanced grid services.

9.5.2 Smart energy services provider and aggregator

The business model of monitoring and controlling large number of resources together by aggregating them and selling their energy and/or capacity in the wholesale or ancillary services markets has been maturing for larger loads and distributed generation. However, **aggregation of batteries from EVs** and offering services that EVs can provide to the market have not yet been fully commercialised.

Profitability and competitiveness of EV flexibility with other flexibility sources at the system level remains a key issue:

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, but high ones are expected in the UK market).
2. **Revenues from ancillary services** may not provide sufficient flexibility in all markets. For instance, the calculation for Germany was based on a market volume of primary and

secondary control of EUR 265 million for 2015, assuming 10 million EVs with 90% availability, representing a value of EUR 29 per EV per year.

Notably, the demand for these services is currently limited to 660 MW, and these 10 million EVs would represent an approximate volume of 30 000 MW, thus pushing the prices even lower.

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. Alternatively, it can be implemented locally as within the charging infrastructure (e.g., local EV-PV synchronisation).
2. **V2G and second-life batteries** operation **require an aggregator**. The original "niche" energy services provider and aggregator model will develop into an energy services platform provider, combining multiple VGI revenue streams and other energy products and services. 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, rather than a focus on a specific application as occurs today.
3. **Virtual Power Plant** operator Next Kraftwerke, and Jedlix, an electric vehicle (EV) aggregator and smart charging platform provider, have launched an international pilot project which uses EV batteries to deliver secondary control reserve to TennET, the transmission system operator in Netherlands. By connecting the EV to the Jedlix platform, Jedlix can coordinate user charging preferences and establish a live connection with the EV, making sure they are charged smartly. Depending on the charging preference, each EV can provide either positive or negative control reserves. Jedlix will be able to combine user preferences, car data, and charging station information to provide a continuous forecast of the available capacity. This is then used by Next Kraftwerke in the bidding process of TenneT for procuring grid services (NextKraftwerke, 2018).
4. The current **Vehicle-grid integration (VGI)** is based largely on the provision of charging management software from developers of proprietary solutions (like AutoGrid or Nuvve) to utilities and fleets, sometimes operated by Original equipment manufacturer (OEMs). The energy services platform provider model is no longer B2B but integrates the software and provides a spectrum of B2C services. The case studies of Enel and Nissan (green box below) illustrate this emerging business strategy from the utility and the OEM perspectives, respectively.
5. But 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). Siemens is using its building automation system Desigo in a research project integrating EVs into the energy management of the building (Siemens, 2017).

Future energy services platform providers: Enel and Nissan strategies

In addition to developing charging infrastructure and bundled offers for home and public charging, Enel has invested in the development of an accessible DC V2X home charging station that charges and discharges at 10 kW. Enel has participated in various pilot projects – for example, in the pilot with Nissan in the UK they have played the role of electricity supplier at the charging point, charging software provider as well as aggregator.

In this pilot, **EV clients received compensation** in the form of a reduction in their electricity bill in exchange for provision of grid services, and, thanks to smart energy service, they locally optimise their consumption by increasing self-consumption of their locally generated solar energy and saving on the network charges. 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. Enel is paid by the transmission and distribution system operators and shares the value with the client.

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). The automaker claims that its solution will allow UK homeowners to **increase the rate of self-consumption** from on-site PV and cut energy bills by up to 66%. Over 880 000 UK homes already have solar panels and the market is growing. This new product is a further extension of **xStorage Home** that Nissan developed in partnership with Eaton with second-life EV batteries.

In October 2017 Nissan announced a partnership with OVO Energy to launch a new offering combining the VNet capability of OVO with Nissan's xStorage Home system to develop an OVO SolarStore and a V2G offering for private customers buying the latest Nissan LEAF (OVO Energy, 2017).

9.6 E-mobility outlook

9.6.1 Cost and competitiveness of EVs

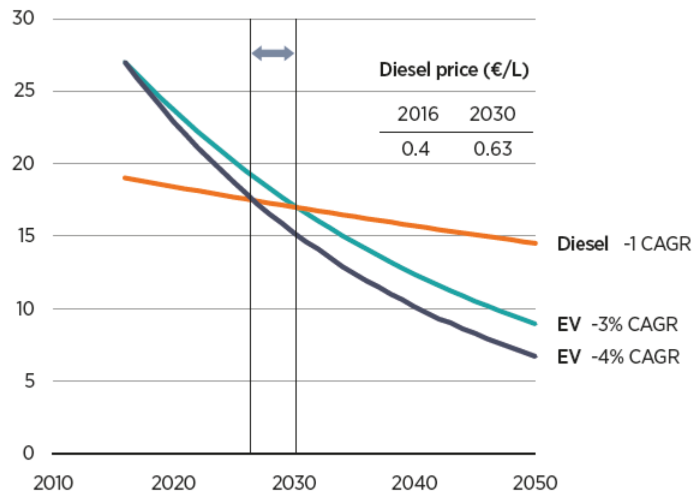
Until now, the most crucial factor that has led to a substantial cost decrease for EVs in the last few years is the **decline in battery pack costs**. Improvements in battery technologies have reduced the average price of battery packs from USD 1 000/kWh in 2010 to around USD 200/kWh in 2017 (UCS, 2017). Analysts expect a further decrease in price to levels of USD 100/kWh in 2025 (McKinsey, 2014), which in turn would result in EVs being competitive with ICE vehicles. As a rule of thumb, this total cost of ownership parity between EVs and conventional gasoline vehicles will be reached at battery prices of around EUR 175/kWh (UCS, 2017).

Another notable factor that has helped to reduce EV prices over the years is the increasing **variety of models** being offered in the market. Whereas in 2010 early customers interested in EVs could choose among only a few limited options – such as the Nissan LEAF, the Citroën C-Zero, etc. – today the range of models is more extensive.

Total cost of ownership (TCO) comparison.

Figure 9.10 shows how the total cost of ownership (TCO) of diesel and EVs could evolve until

Figure 9.10: Total cost of ownership (TCO) for electricity and diesel-powered cars until 2050



Source: IRENA (2019a)

2050. The graph, although illustrative, aims to emphasise that in the medium term (the second half of the 2020s) EVs will eventually be more competitive than diesel vehicles even without subsidies and taxes. If that is the case, EVs could reach a global flee penetration of 7% (IEA, 2018a).

The continued decrease in TCO is supported by the same trends described earlier and can be strengthened by **two more observations**. On the one hand, because of **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. This will inevitably increase the EV utilisation rate to ranges from 40 000 to 55 000 km per year, and will in turn increase the EV's fuel cost savings in comparison with a diesel car driving the same yearly mileage.

On the other hand, an **unknown variable is how quickly the TCO of EVs will go down in comparison with diesel vehicles**. This point could be influenced by the recent and upcoming wave of countries 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).

9.6.2 Outlook of batteries

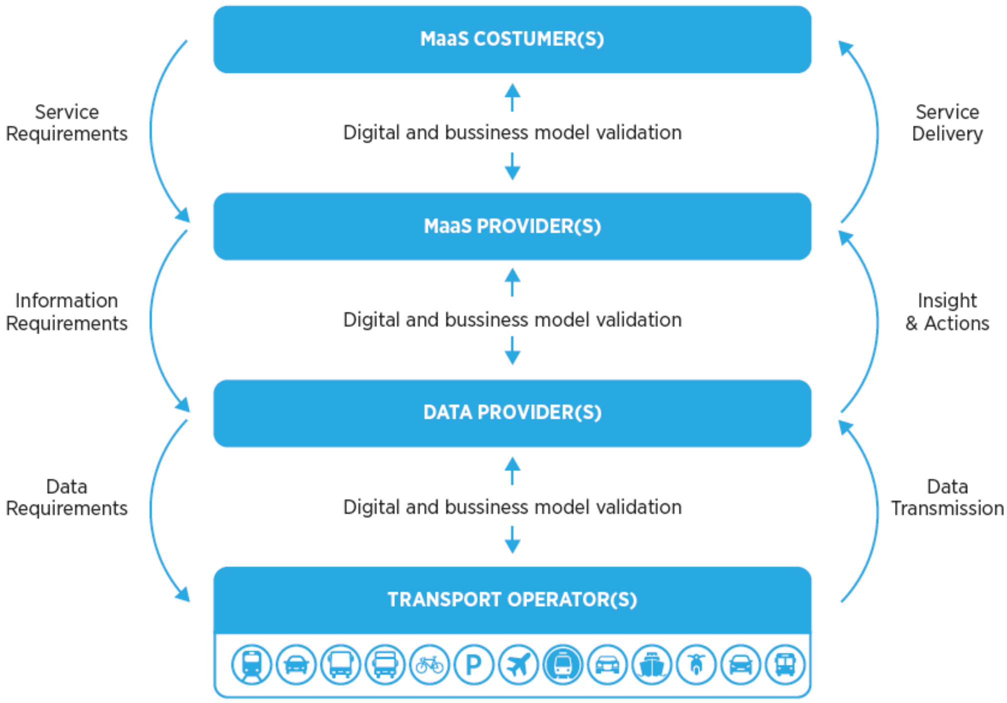
While **Li-on will probably remain the prevalent technology until 2030**, potential breakthroughs in other technologies may lead to its replacement in the long-term horizon.

Two technologies that have already been commercialised – for example, as minor technologies in e-buses for around 10 years – are **Zeolite Battery Research Africa (ZEBRA)** and **lithium-metal-polymer (LMP)** battery technologies.

Other technologies with lower maturity levels are currently under development (only cells are sold, not systems) and could be potentially disruptive if their issues are solved, including:

- Li-ion systems with silicon (Si) as a negative electrode
- Lithium-sulphur system (Li-S)
- Sodium-ion batteries (Na-ion), which are raising interest due to the potential low cost and environmental friendliness

Figure 9.11: Simplified mobility-as-a-service value chain



Source: IRENA (2019a)

- Metal-air batteries including aluminium-air (Al-air) and zinc-air (Zn-air)
- Redox flow batteries for mobility applications.

9.6.3 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)**.

Mobility-as-a-service is a way to seamlessly combine transport alternatives from various providers (including shared mobility providers but beyond). MaaS goes beyond calculating the fastest path from one place to another and instead offers a one-stop shop for everything from optimised travel itineraries to payments. A MaaS offering thus consists of **four complementary functionalities**: **trip planning**, **booking**, **payment** and **ticketing/billing**.

At the centre of the MaaS design are **four main actors**, each of them having a key role in providing the MaaS offering. These actors are the **customers**, the **MaaS providers**, the **data providers** and the **transport operators** (figure 9.11).

Although customers have progressively adopted new mobility possibilities over the last decade, and while transport operators are already in place in many countries, MaaS providers and data providers remain almost non-existent. The following section and Figure 28 clarify the value that each step of the value chain offers to the customer.

9.7 Hydrogen versus Electric vehicles

The Truth about Hydrogen

9.8 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 explain the **main challenges for the profitability** of EV flexibility?
7. 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.
8. Can you explain the main actors that determine the **e-mobility business model**? **customers**, the **MaaS providers**, the **data providers** and the **transport operators**

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