Energy Storage

4. Electric Vehicles as Energy Storage Providers

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EV History

- In 1828 Hungarian inventor Ányos Jedlik invented one of the first electric motors and constructs a model car supplied by this motor.
- In 1835 prof. Sibrandus Stratingh from Groningen and his assistant Christopher Becker construct a small EV supplied by primary batteries.
- In 1881 William Ayrton and John Perry construct the first EV in order to advertise their inventions.
The concept of EV battery swap was already suggested in 1896.

Delivery vehicle (furgon) was purchased without the battery.

An owner would pay a monthly fee and per mile fee.

This was in business in period 1910-1924.
Fall and Rise of EVs

- Modern, quick highways, along with the development of electric starter, problems with large distances and long charging times resulted in bust of the EV industry.
- Years later, the oil crisis during the 1970 and 1980 spur a new interest in EVs.
- During 1990 and 2000, due to the acceptance of responsibility for our planet, this interest has further increased.
First Modern EV

- General Motors EV1
- First modern BEV from a major automaker

Battery
- Early versions: lead-acid, 16.5–18.7 kWh
- Later versions: NiMH, 26.4 kWh

- Range: 70 miles (110 km)
- Almost all vehicles ultimately withdrawn and destroyed
Battery EVs Today

- They use exclusively chemical energy stored in rechargeable batteries
- Number one most selling EV is Nissan Leaf with over 370,000 sales
<table>
<thead>
<tr>
<th>EV model</th>
<th>Battery Capacity (kWh)</th>
<th>Range (km)</th>
<th>OBC Max Power (kW)</th>
<th>OBC Type</th>
<th>DC Max Power (kW)</th>
<th>FC Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitsubishi i-MiEV</td>
<td>16</td>
<td>160</td>
<td>3,7</td>
<td>T1</td>
<td>50</td>
<td>CDM</td>
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<tr>
<td>Citroen C Zero</td>
<td>16</td>
<td>88</td>
<td>3,7</td>
<td>T1</td>
<td>40</td>
<td>CDM</td>
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<tr>
<td>Peugeot iOn</td>
<td>16</td>
<td>88</td>
<td>3,7</td>
<td>T1</td>
<td>40</td>
<td>CDM</td>
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<tr>
<td>Smart ED</td>
<td>17,6</td>
<td>161</td>
<td>7</td>
<td>T2</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Chevrolet Volt</td>
<td>18,4</td>
<td>85</td>
<td>7,2</td>
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<td>VW e-up</td>
<td>18,7</td>
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<td>50</td>
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<td>Fiat 500e</td>
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<td>6,6</td>
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<td>Honda Clarity</td>
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<td>143</td>
<td>7,2</td>
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<td>Hyundai Ioniq Electric</td>
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<td>200</td>
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<td>Kia Soul EV</td>
<td>33</td>
<td>179</td>
<td>6,6</td>
<td>T2</td>
<td>100</td>
<td>CDM</td>
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<tr>
<td>BMW i3</td>
<td>33</td>
<td>183</td>
<td>11</td>
<td>T2</td>
<td>50</td>
<td>CCS</td>
</tr>
<tr>
<td>Ford Focus Electric</td>
<td>33,5</td>
<td>185</td>
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<td>T2</td>
<td>50</td>
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<td>VW e-golf</td>
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<td>192</td>
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<td>40</td>
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<tr>
<td>Nissan Leaf</td>
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<td>243</td>
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<td>CDM</td>
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<td>Renault Zoe</td>
<td>41</td>
<td>299</td>
<td>22</td>
<td>T2</td>
<td>43</td>
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<tr>
<td>BMW i3 (120 Ah)</td>
<td>42,2</td>
<td>233</td>
<td>11</td>
<td>T2</td>
<td>50</td>
<td>CCS</td>
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<tr>
<td>Tesla Model 3</td>
<td>60</td>
<td>370</td>
<td>11</td>
<td>T2</td>
<td>70</td>
<td>SC</td>
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<tr>
<td>Chevrolet Bolt</td>
<td>60</td>
<td>383</td>
<td>7,2</td>
<td>T2</td>
<td>50</td>
<td>CCS</td>
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<tr>
<td>Hyundai Kona E</td>
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<td>415</td>
<td>7,2</td>
<td>T2</td>
<td>80</td>
<td>CCS</td>
</tr>
<tr>
<td>Tesla Model 3 (LR)</td>
<td>75</td>
<td>499</td>
<td>11</td>
<td>T2</td>
<td>110</td>
<td>SC</td>
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<tr>
<td>Tesla Model S 75D</td>
<td>75</td>
<td>417</td>
<td>17</td>
<td>T2</td>
<td>120</td>
<td>SC</td>
</tr>
<tr>
<td>Tesla Model X 75D</td>
<td>75</td>
<td>381</td>
<td>17</td>
<td>T2</td>
<td>120</td>
<td>SC</td>
</tr>
<tr>
<td>Jaguar I-Pace</td>
<td>90</td>
<td>37,5</td>
<td>7,4</td>
<td>T2</td>
<td>100</td>
<td>CCS</td>
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<tr>
<td>Tesla Model X 100D</td>
<td>100</td>
<td>475</td>
<td>17</td>
<td>T2</td>
<td>120</td>
<td>SC</td>
</tr>
<tr>
<td>Tesla Model X P100D</td>
<td>100</td>
<td>465</td>
<td>17</td>
<td>T2</td>
<td>120</td>
<td>SC</td>
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<tr>
<td>Tesla Model S 100D</td>
<td>100</td>
<td>539</td>
<td>17</td>
<td>T2</td>
<td>120</td>
<td>SC</td>
</tr>
<tr>
<td>Tesla Model S P100D</td>
<td>100</td>
<td>507</td>
<td>17</td>
<td>T2</td>
<td>120</td>
<td>SC</td>
</tr>
</tbody>
</table>
Croatian EV Industry

- Croatian industry has its EVs:
  - Loox by Dok-Ing
  - Concept One and Two by Rimac
Battery EVs Today

- Tesla Motors is the only car producer investing in infrastructure as well
- 1,229 supercharger stations with 9,623 superchargers worldwide
Types of electric vehicles

- **HEV**
  - Hybrid Electric Vehicle
  - Combine traditional ICE (Internal Combustion Engine) with battery driven electric motor

- **PHEV**
  - Plug-in Hybrid Electric Vehicle
  - Can be plugged-in to recharge battery
  - Typically has higher electric autonomy than HEVs

- **BEV**
  - Battery Electric Vehicle
  - No ICE
  - Often referred to simply as EV
Hybrid vehicle drivetrain

- Main types of drivetrains
  - Parallel hybrid
  - Series hybrid
  - Series-parallel (power-split) hybrid

- Regenerative breaking – all hybrid configurations including BEVs make use of regenerative breaking
Parallel hybrid

- Typically used by HEVs
- Relies mostly on ICE
- Typically has relatively small battery
- ICE and electric motor act simultaneously – they are connected to the same shaft and their torques act together
- ICE may also be used for recharging battery
Series hybrid

- Typically used by PHEVs
- Larger battery than parallel hybrid – higher cost
- Smaller ICE
  - Often referred to as "range extender"
  - Drives the generator
  - Not mechanically connected to the wheels
Series-parallel (power-split) hybrid

- ICE drive and electrical drivetrain can be decoupled allowing for ICE-only or electric-only drive
- Combines favorable characteristics
  - Series – more efficient at lower speeds
  - Parallel – more efficient at higher speeds
- Higher cost
EV Charging
Introduction

- Charging is required by:
  - Battery Electric Vehicles (BEV)
  - Plug-in Hybrid Electric Vehicles (PHEV)

- In the following slides term Electric Vehicles (EV) implies both BEV and PHEV

- AC grid vs. DC battery

- Charger
  - AC/DC converter
  - Unidirectional
  - Bidirectional

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Types of EV Charging

- **AC Charging**
  - On-board charger
  - "Slow" charging

- **DC Charging**
  - Off-board charger
  - "Fast" charging
AC Charging

- On-board chargers usually have lower power:
  - Lower than 20 kW
  - Typically 3.3 – 6.6 kW

- High power on-board chargers are feasible, but have several downsides:
  - Bulkier than low power chargers thus taking more space and adding weight to an EV
  - Higher price of power electronics
DC Charging

- Off-board chargers usually have higher power:
  - Higher than 20 kW
  - Typically 20 – 100 kW

- Off-board placement allows for increased charger dimensions and weight

- DC charging stations are much more expensive compared to AC charging stations
Typical Charging Times

<table>
<thead>
<tr>
<th>Charger power</th>
<th>Type of charging</th>
<th>Charging time (cca.)</th>
<th>State-of-charge (SOC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6 kW</td>
<td>AC (on-board charger)</td>
<td>9 hours</td>
<td>0-100 %</td>
</tr>
<tr>
<td>6.6 kW</td>
<td>AC (on-board charger)</td>
<td>5 hours</td>
<td>0-100 %</td>
</tr>
<tr>
<td>40kW</td>
<td>DC (off-board charger)</td>
<td>30 minutes</td>
<td>0-80 %</td>
</tr>
</tbody>
</table>

107 miles = 172 km
Standards

- IEC 61851 *Electric vehicle conductive charging system*
- IEC 62196 *Plugs, socket-outlets, vehicle connectors and vehicle inlets – Conductive charging of electric vehicles*

- IEC 61851 prescribes:
  - 3 EV connection cases (using cables and plugs)
  - 4 EV charging modes

Terminology:
EV Connection Cases

- **Case A**
  - Cable permanently attached to the vehicle
  - Not very common

- **Case B**
  - Both sides of cable are detachable

- **Case C**
  - Cable permanently attached to the EVSE (Electric Vehicle Supply Equipment)
EV Charging Modes

- **Mode 1**
  - Direct connection to standardized residential socket-outlets
  - Electrical installation must have an earthing system, circuit breaker etc.
  - Prohibited in some countries, e.g. USA (due to lack of earthing in some residences)
  - Voltage limits (AC): 250 V (1-phase), 480 V (3-phase)
  - Current limit: 16 A
EV Charging Modes

- **Mode 2**
  - Connection to standardized residential socket-outlets
  - In-cable Control and Protective Device (IC-CPD) – performs control and safety functions
  - Voltage limits (AC): 250 V (1-phase), 480 V (3-phase)
  - Current limit: 32 A
EV Charging Modes

- **Mode 3**
  - Connection to dedicated EVSE
  - EVSE (Electric Vehicle Supply Equipment)
    - Permanently connected to the AC supply network
    - Incorporates control and safety functions
  - On-board charger is used (AC charging)

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EV Charging Modes

- **Mode 4**
  - Connection to dedicated EVSE
  - **EVSE (Electric Vehicle Supply Equipment)**
    - Permanently connected to the AC supply network
    - Incorporates control and safety functions
    - Incorporates an off-board charger (DC charging)
  - Only case C connection is allowed

![Diagram of EV charging process]
Control and Safety Functions (Pilot Functions)

- Mandatory functions for modes 2, 3 and 4
  - Verification that the vehicle is properly connected
  - Continuous protective earth conductor continuity checking
  - Energization of the system
  - De-energization of the system

- Optional functions for modes 2, 3 and 4
  - Selection of charging rate
  - Determination of ventilation requirements
  - Mechanical retaining/releasing of the coupler
  - Control of bi-directional power flow
  - Other
Pilot functions – example

- This example refers to Mode 2 and Mode 3 charging according to the SAE J1772 standard

- Pins:
  - L1 – Mains 1
  - L2/N – Mains 2 / Neutral
  - PE – Protective Earth
  - CP – Control Pilot
  - CS – Connection Switch

- CS – ”proximity detection” function – used to signal correct insertion of the connector to the inlet
- CP – see next slide
# Pilot functions – example

<table>
<thead>
<tr>
<th>EV state</th>
<th>Va</th>
<th>S2</th>
<th>EV resistance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12 V</td>
<td>open</td>
<td>-</td>
<td>EV not connected</td>
</tr>
<tr>
<td>B</td>
<td>9 V</td>
<td>open</td>
<td>2.74 kΩ</td>
<td>EV connected</td>
</tr>
<tr>
<td>C</td>
<td>6 V</td>
<td>closed</td>
<td>2.74 kΩ</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>3 V</td>
<td>closed</td>
<td>2.74 kΩ</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0 V</td>
<td>open</td>
<td>-</td>
<td>Error</td>
</tr>
<tr>
<td>F</td>
<td>- 12 V</td>
<td>open</td>
<td>-</td>
<td>EVSE not available</td>
</tr>
</tbody>
</table>

[Source: IEC 61851-1:2012](https://www.iec.ch/publications/iekc Perry)
Pilot functions – example

- EVSE signal generator gives either steady state 12 V DC or a PWM signal
- EVSE indicates maximum available current by varying PWM duty cycle
- Current profile is determined by the vehicle

Source: IEC 61851-1:2012
Coupler Types

- IEC Type 1
  - SAE J1772 Type 1 (AC)
  - SAE J1772 Combo 1 (AC+DC)

- IEC Type 2
  - Type 2 (AC)
  - Combo 2 (AC+DC)

- CHAdeMO (DC)

- Tesla Charging (AC+DC)

- GB/T (China)
  - 20234.2-2011 (AC)
  - 20234.3-2011 (DC)

Coupler = Connector + Inlet
Coupler Types

Source: ev-institute.com
Type 1

- SAE J1772 (North American standard)
- Complies with IEC 62196
- Used in North America and Japan
- AC (1-phase)
- AC Level 1
  - Power up to 1.9 kW (120V, 16A)
- AC Level 2
  - Power up to 19 kW (240V, 80A)
- Pins:
  - L1, L2/N – Mains / Neutral
  - PE – Protective Earth
  - CP – Control Pilot
  - CS – Connection Switch (proximity detection)
Combo 1

- Same as Type 1, but with DC pins added
- Combined Charging System (CCS)
- AC (1-phase) + DC
- DC Level 1
  - Power up to 48 kW (600V, 80A)
- DC Level 2
  - Power up to 120 kW (600V, 200A)
Type 2

- VDE-AR-E 2623-2-2 (German standard)
- Commonly referred to as "Mennekes"
- Complies with IEC 62196
- Used in Europe
- AC (1-phase or 3-phase)
  - AC 1-phase
    - Power up to 14 kW (230V, 63A)
  - AC 3-phase
    - Power up to 43 kW (400V, 63A)
- Pins:
  - L1, L2, L3, N – Mains, Neutral
  - PE – Protective Earth
  - CP – Control Pilot
  - PP – Proximity Pilot (proximity detection)
Combo 2

- Same as Type 2, but with DC pins added
- Combined Charging System (CCS)
- AC (1-phase or 3-phase) + DC
- DC power up to 200 kW (1000V, 200A)
**CHAdEMO**

- Specified by JEVS (Japanese standard)
  - Developed by Tokyo Electric Power Company (TEPCO), Nissan, Mitsubishi, Fuji Heavy Industries and Toyota
- Complies with IEC 62196
- Used mostly in Japan, but also in Europe and USA
- DC only
  - Power up to 120 kW (600V, 200A)
- Pins:
  - CP, CP2, CP3 – Control Pilot
  - COM1, COM2 – Communication (+/−)
  - IM – Isolation Monitor
  - CS – Connection Switch (proximity detection)
Tesla Charging

- Designed for Tesla EVs
- Used in USA
- AC (1-phase) + DC
- AC power up to 19 kW (240V, 80A)
- DC power up to 125 kW (500V, 250A)
- Term "supercharger" refers to fast DC chargers

Remarks:
- In Europe, Tesla uses Type 2 connector for both AC and DC (not Combo2)
- Various adapters available (e.g. CHAdeMO)
Chinese standards:

- GB/T 20234.2-2011 (AC)
- GB/T 20234.3-2011 (DC)

AC 1-phase

- Power up to 7 kW (220V, 32A)

AC 3-phase

- Power up to 21 kW (400V, 32A)

DC

- Power up to 187 kW (750V, 250A)
Examples

Coupler: Combo 2
Example – Nissan Leaf

Inlets: CHAdeMO and Type 1

Electric Car Charging

Faster is Better
(usually)
Example – Renault Zoe

Inlet: Type 2
Example – Tesla Model S

Inlet: Tesla
Example – Tesla

Tesla charging station

Connector: Tesla
Battery Swapping
Remaining Problems

- Long charging times
- Widespread utilization of fast chargers is not sustainable from the perspective of the power system, and it is also still slower than the gas station
- The situation is still much worse as compared to the infrastructure for internal combustion engine power vehicles – infrastructure investments needed
Remaining Problems

- The most widespread battery technology is Lithium-ion
- The price of new battery is around 10,000 USD (500-600 USD/kWh)
- Batteries degrade with usage and time – the best state-of-health indicator is capacity
- EV manufacturers account for capacity fade:

Source: batteryuniversity.com
Battery Swapping Stations (BSS) swap depleted batteries with fully charged ones.
(The Final) Part of the Solution?

- Battery in a Tesla S Model chassis
- The 85kWh battery has 7,616 18650 cells in parallel/serial configuration
- At $250 per kWh, the cost is lower than other Li-ion designs

Source: batteryuniversity.com and Tesla motors
(The Final) Part of the Solution?

- BSS – the concept that requires the least changes compared to the current driving habits
- In case of many BSSs, there is no long waiting time to charge the EV and no range anxiety – actual substitute for gas stations
- The most common BSS model – batteries are owned by the BSS and leased to the customers
  - Initial investment reduced by the price of the battery (20% - 40% of total EV’s price)
  - Additionally, users that use only BSS do not have to invest in home charging equipment
(The Final) Part of the Solution?

- Since batteries are owned by the BSS the customer does not need to worry about:
  - Maintenance cost or battery lifetime
  - Battery degradation problem
  - Charging speed (fast charging degrades batteries more than slow charging)

- All these costs need to be considered when a BSS charges its service fee to end-clients
BSS Business Model

- BSSs are new players in electricity markets
- The BSS energy storing policy is based on time-changing prices: real-time pricing (RTP)
- BSS maximizes its profits by utilizing periods of low prices to charge its batteries in Grid-to-Battery (G2B) mode, and periods of high prices to discharge its batteries in Battery-to-Grid (B2G) mode
- Additionally, a BSS can perform Battery-to-Battery (B2B) discharging some of its batteries in order to fully charge others
BSS Business Model


Battery Swapping Station

Electricity Market

Power System
BSS Business in Practice

- Better Place
  - Launched in 2008. in partnership with Renault-Nissan
  - Used the same technology to swap batteries that F-16 jet fighter aircraft use to load their bombs
  - Started commercialization in six countries
  - Filed for bankruptcy in 2013.

- Tesla
  - Introduced battery swapping technology for their EVs in 2013.
  - Project has been put on hold

- Other emerging BSS providers
  - BattSwap
  - …
Survey on EVs and BSSs

☐ An on-line survey on electric vehicles and battery swapping stations

☐ The survey has two main goals:
  ■ Identifying problems and reasons that make people defer their purchase of an EV
  ■ Gaining insight into people’s perception of battery swapping

☐ The questions were formulated in a way that both current and potential EV owners can answer them
Survey – sample description

Age of the respondents

- 18-29: 50%
- 30-39: 30%
- 40-49: 10%
- 50-59: 5%
- 60-69: 2%
- 70-79: 1%

Total answers: 778

Gender of the respondents

- Female: 50%
- Male: 50%

Total answers: 779

Continents of the respondents

- Europe: 85%
- North America: 5%
- South America & Central America: 3%
- Africa: 2%
- Asia: 1%
- Australia & Oceania: 1%

Total answers: 779
Survey – sample description

Type of current car

- Electric Vehicle (EV)
- Plug-in Hybrid Electric Vehicle (PHEV)
- Hybrid Electric Vehicle (HEV)
- Non-electric Vehicle

Total answers: 759

Kilometers traveled per year

- Over 50 000
- 40 000 - 50 000
- 30 000 - 40 000
- 20 000 - 30 000
- 10 000 - 20 000
- Under 10 000

Total answers: 679
Survey – results

What is your general stand on the future of EVs?

- They will completely replace gasoline-powered cars in the following years
- They will be a part of the transportation system, but will never take over the throne from the gasoline-powered vehicles
- They will always remain a toy for enthusiasts

Total answers: 676

By which year do you think you will own an EV?

- After 2050
- By 2050
- By 2040
- By 2030
- By 2025
- By 2020

Total answers: 567
Survey – results

What is the main reason for you not to buy an EV?

- Not interested in a new car at all / I am perfectly satisfied with my current vehicle
- High investment cost
- Afraid of the new technology
- Lack of public charging infrastructure
- Lower range with fully charged EV compared to a fully tanked gasoline vehicle
- Something else

Total answers: 652

How much more would you be willing to pay for a new EV instead of a new gasoline-powered vehicle?

- Up to 100%
- Up to 50%
- Up to 25%
- Up to 10%
- 0%

Total answers: 667
Assuming EVs reduce the cost per 100 km (62 miles) of driving (initial car price and maintenance cost neglected), how much reduction would be enough for you to switch to an EV?

- Up to 100%
- Up to 50%
- Up to 25%
- Up to 10%
- 0%

Total answers: 659

Not considering the price, would you switch to an EV if your driving comfort would remain exactly the same as with your current vehicle?

- Yes
- No
- Maybe

Total answers: 671
Survey – results

Would you switch to an EV if the transition would be seamless in terms of the available infrastructure and your driving habits (distances you drive, intervals of stopping etc.)?

- Yes
- No
- Maybe

Total answers: 653

What driving radius do you expect from an EV?

- Over 800 km
- 500 - 800 km
- 250 - 500 km
- 100 - 250 km
- Under 100 km

Total answers: 624
In case you owned an EV, would you be able to charge it at home, e.g. in your garage or on your parking lot?

Yes

No

Total answers: 643

In case you went on a longer trip with an EV, would you consider using only superchargers, i.e. pulling over for half an hour every 250 km (cca. 150 miles) in order to recharge, or would you insist on using a battery swapping station as a mean for receiving a full charge within 2 minutes?

- I am perfectly fine with only superchargers
- I would like to have a choice, but I would always use a supercharger if that is a cheaper option
- I would definitely use a battery swapping station whenever I can, even if it is more costly than the supercharger

Total answers: 654
Survey – results

Would you be willing to prolong your business trip timewise, as a consequence of having to pull over every 250 km (cca. 150 miles) in order to supercharge?

- Yes
- No

Total answers: 640

Would you be more likely to buy an EV if you could purchase it without the battery pack (i.e. the investment is reduced by 40%) and then lease the batteries from the battery swapping station? Imagine that there are many battery swapping stations around.

- Yes
- No

Total answers: 643
Survey – results

How much more would you be willing to pay for a battery swap compared to the price of supercharging?

- Up to 100%: 1%
- Up to 50%: 10%
- Up to 25%: 30%
- Up to 10%: 34%
- 0%: 25%

Total answers: 638

In your day-to-day life, how often would you charge your EV at home (assuming you have the infrastructure)?

- Every night because I do not want to calculate with my driving range: 10%
- In case I know I have enough charge for the next day, I will not charge, i.e. every two days: 40%
- Only when I am about to fully deplete my battery, i.e. every four days: 50%

Total answers: 640
Survey – results

In your day-to-day life, how often would you use battery swapping stations?

Never, because I would charge only at home and at public charging locations. I would plan ahead so that I never have to pay additional cost for using a swapping station.

I would mostly use home and public charging stations. However, I do not want to plan ahead all the time so I would use battery swapping service when in need.

I would mostly use battery swapping station, either because of lack of charging infrastructure or simply because it is more convenient for me.

Total answers: 639

In case of the same price, would you rather use a supercharger or a swapping station?

Supercharger

Swapping station

Whichever is the closest

Total answers: 623