Making sense of the data

data analysis techniques of electric vehicle charging behaviour

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2. Outline

2.1. Scope

Charging an electric vehicle needs to be as simple as possible for the user. He needs to park his car, plug his vehicle and identify to start charging. There is no need to understand the technology and protocols needed to reach this simple task.
For the students and researchers of the Amsterdam University of Applied Science (AUAS / HvA), there is a need to understand as deep as possible all the techniques involved in this technology.
The purpose of this document is to give to the reader the information he needs to understand how an electric car can be charged and how he can use these knowledges to analyses and interpret data.

2.2. Nomenclature

Table 1: Symbols used in this document

Symbols	Descriptions
AC	Alternating Current
t	Time in second
V	Volt
A	Ampere
P	Power (in Watt)
E	Energy (in Watt hour – Wh)
V_{LL}	RMS line to line voltage in a three-phase system
$V_{NL} = -V_{LN}$	RMS neutral to Line voltage in a three-phase system
I_{LL}	Current going through the load in three phases delta configuration
I_{NL}	Current going through the load in three phases star configuration
P_{LL}	Power in the load in three phases delta configuration
P_{NL}	Power in the load in three phases star configuration
RFID	Radio-frequency identification
CDR	Charging data record

2.3. Purpose

This document is written in the frame of the SEEV4-city Flexpower pilot. The purpose it is to summarise the knowledges accumulated during this operational pilot on the charging of electric vehicles. From this knowledge, it is possible to understand the techniques used to treat and interpret the data collected in the IDO-laad [1].
The Flexpower pilot is in Amsterdam, the Netherlands, and uses public chargers following the mode 3 of the IEC 61851-1.

3. Charging electric vehicles

The International Electrotechnical Commission (IEC) published the IEC 61851-1 defining 4 different charging modes with their capabilities.

3.1. Mode 1

The vehicle is connected to a standard AC outlet up to 3 phases with earth. The delivered current goes up to 16 A per phase. There is no other protection than the protection already installed in the building. This mode uses the internal charger of the vehicle.

3.2. Mode 2

Like the mode 1, the mode 2 uses standard AC outlet with earth and is installed on the main circuit of a building. However, a specific cable with embedded protection is required. The current is limited to 32 A per phase. This mode uses the internal charger of the vehicle.

3.3. Mode 3

A specific charger is installed and permanently connected to AC network. When connected, there is constant communication between the charge point and the vehicle. The norm doesn't define a maximum current per phase. In practice it is generally 32 A or 64 A in some specific cases. This mode uses the internal charger of the vehicle.

3.4. Mode 4

A specific charger is installed. It contains an AC to DC converter instead of using the one embedded in the vehicle. The DC charger is thus directly connected to the battery management system and continuously communicate with it. High charging speed can be achieved (up to 350kW).

4. Charging speeds

4.1. Voltage

In the Netherlands, the nominal voltage, V_{NL}, is standardized to 230 V with a frequency of 50 Hz. The voltage can vary of ±10% from the nominal value (from 207 to 253V [2]). The voltage variation has a direct influence on the charging power of the vehicle (see section 4.3).
The voltage variation is linked with the length of the electric cable between the point of consumption and the local transformer. The longer the distance, the higher the voltage drop. The power requested from the local network is also of influence. Paradoxically, the more power is requested, the lower is the voltage obtainable and the less power is available.
On the other hand, the installation of sun panels has a positive influence of the voltage. The higher the power delivered by the sun panels in the local network, the higher will be the voltage and the available power.

4.2. Current

The current delivered by the mode 3 charging stations (see paragraph 3.3) might vary according to two limitations:

- The maximum current the vehicle demands.
- The maximum current allowed by the charging station

The lowest of the two is used to limit the current.

4.2.1. Current limitation from the vehicle

The embedded charger in the vehicle has a maximum current it can manage to charge the battery. From the information collected on the ev-database website [3], 7 different nominal charging currents were found for various vehicles. They are listed in the first column of the Table 2. An example of vehicle using this nominal current is given in the second column. These 7 values are reduced to three main currents categories and reported in the same table in the second column.

Table 2: Identified nominal charging currents for electric vehicles.

EV Database current (A)	Example vehicle	Categories current (A)
14	Nissan Leaf	16
16	Citroen C-Zero	
20	Smart ForFour Electric Drive	25
24	Tesla Model S	
29	Opel Grandland X Hybrid4	32
31	Volkswagen e-Up!	
32	Renault Zoe ZE50 R135	

These three categories will be used further in this document to identify the vehicles.

4.2.2. Current limitation from the charging station

The current limitation from the charging station is a parameter the charging station operator defines based on the maximum current the local low voltage network can deliver.
This maximum charge current is communicated to the vehicle via a special wire in the connector. The detail of the communication protocol is defined in the IEC 61851-1 and might vary from 6 A to 80 A per phase.
For each nominal current, a variation is allowed by the norm. Table 3 shows the computed current intervals for several nominal currents.

Table 3: Current variation allowed by the IEC 61851-1

Current (A) per phase			
Minimum	Nominal	Maximum	Tolerance
4.5	6	7.5	±25%
6.5	8	9.5	±19%
14.5	16	17.5	±9%
23.5	25	26.5	±6%
30.5	32	33.5	±5%
78.5	80	81.5	±2%

This tolerance is due to communication mean between the charging station and the vehicle, carried by a 1 kHz pulse width modulation (PWM). Electronic components have a tolerance, influencing the generated signal. It is to notice that because the variation is an absolute value, the percentage diminish with the increase of the current. If the voltage remains the same, the power charging the battery vehicle will vary in the same proportions as the current. Further explanation can be found in the following chapter.

4.3. Power

4.3.1. Single phase

In an electrical system, the power is defined by the product of the voltage (V) by the current (I).

$$P = V \cdot I$$

A vehicle connected to the low voltage network with a maximum charging current of 16 A will charge at:

$$P = 230 \cdot 16 = 3680\ W \approx 3.7\ kW$$

4.3.2. Three phases

In a three phase system, two architectures are commonly used, the star and the delta. In the star the voltage V_{NL} applied to the load is between the neutral (N) and a phase or line (L), whereas in the delta the voltage V_{LL} is between two phases or lines. As a result:

$$V_{\mathrm{LL}} = V_{NL} \cdot \sqrt{3}$$

If the current is limited by the grid connection, it can be demonstrated that the current in the load in the delta configuration is $\sqrt{3}$ lower than in the star configuration. Therefore:

$$I_{\mathrm{LL}} = \frac{I_{NL}}{\sqrt{3}}$$

The power is thus:

$$P_{\text{LL}} = 3 \cdot V_{\text{LL}} \cdot I_{\text{LL}} = 3 \cdot V_{NL} \cdot \sqrt{3} \cdot \frac{I_{NL}}{\sqrt{3}} = 3 \cdot V_{\text{NL}} \cdot I_{\text{NL}} = P_{\text{NL}}$$

Because the power remains the same in both configurations, we have:

$$P = P_{\text{LL}} = P_{\text{NL}}$$

A vehicle with three phases capacity and 16 A can charges with:

$$P = 3 \cdot 230 \cdot 16 = 11040\ W \approx 11\ kW$$

4.3.3. Multiple phases

The formula above can be generalised for a system with N phases and becomes:

$$P = N \cdot V \cdot I$$

4.3.4. Electric vehicles charging power

From the categorisation in the section 4.2.2 and the phases configurations found in the ev-database, the vehicles are grouped in 6 categories according to their nominal charging powers and currents. These categories are shown in the Table 4.

Table 4: Powers for various currents limits and phases configuration

Current (A)	1 Phase	2 Phases	3 Phases
16	3.7 kW	7.4 kW	11 kW
25	-	-	17 kW
32	7.4 kW	-	22 kW

4.3.5. Power variations

Due to the variations in voltage and current, the power measured during the charge will also vary. The Table 5 show the variations for three phases and 16 A charging capabilities vehicles.

Table 5: Charge power variations for a 11kW vehicle.

Power (kW)		Voltage (V)		
		207	230	252
Current (A)	14.5	9	10	11
	16	9.9	11	12.1
	17.5	10.9	12.1	13.2

At nominal charge power, the vehicle can see the power to charge the vehicle to varying from 9 kW up to 13.2kW whereas the nominal power is 11 kW. A variation of ±18% regarding to this nominal power. This variation needs to be taken in consideration during the vehicle identifications.

4.3.6. Other parameters

In combination with the parameters previously explained in detail, some other have an influence on the power the battery can charge:

- Thermal limitation in the embedded charger or battery. This is linked with the ambient temperature. A vehicle standing in the hot summer sun might charge slowly to avoid overheating.
- Control of the power factor from the grid connection.
- Reduction of the power commanded by the network frequency. If the frequency drops, the power might decrease to help sustaining the distribution network.

The detailed influence on the power delivered by the charging station or absorbed by the battery is left at the respective discretion of the cars and charging poles manufacturers.

4.4. Energy and batteries capacity

The battery capacity of the vehicle is defined in Wh or kWh. As defined in the unit, the Wh is a function of power (W) and time (hour). A battery with a capacity of 1 kWh can deliver 1 kW during 1 hour before it is depleted. At the reverse, to fully charge a 1 kWh battery, the power supply delivers 1 kW for 1 hour. In both cases, it is assumed no losses and that the battery can be charged up to the end at nominal power.

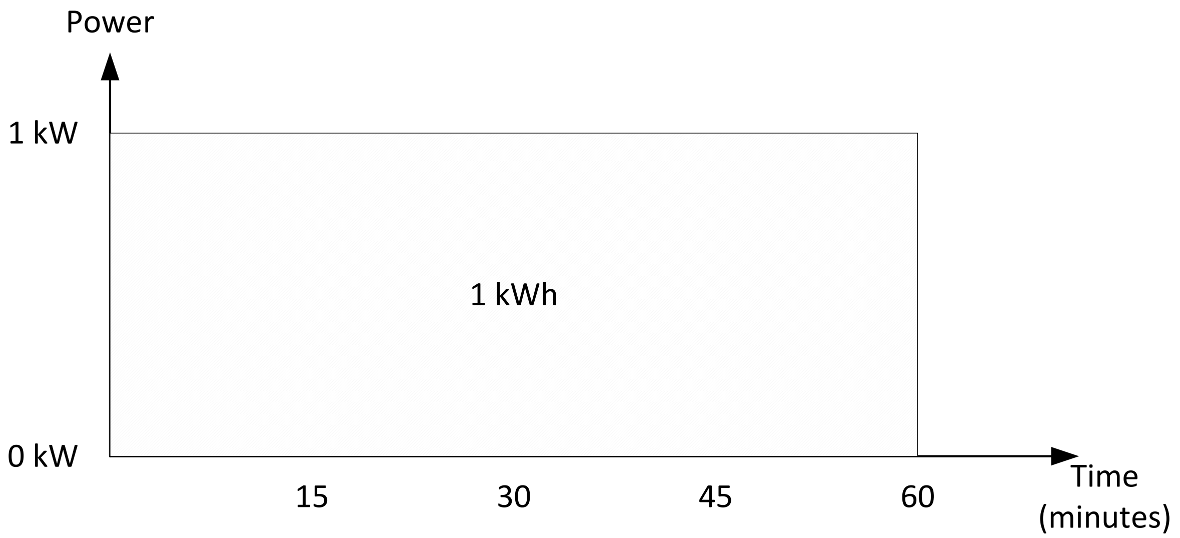

Figure 1: Graphical relation between power and energy

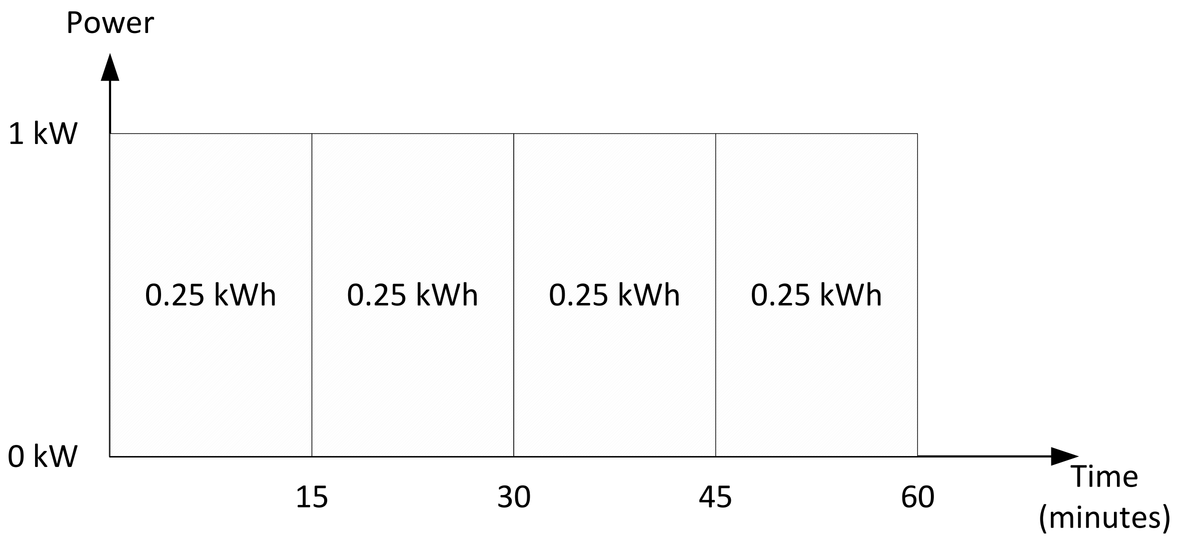

Figure 2: Even of the power is constant, the energy will vary according to the duration it is applied.

The relation between the energy variation ΔE, the power and interval (in minute) is defined with:

$$\Delta E = P \cdot \frac{Interval}{60} \Leftrightarrow P = \Delta E \cdot \frac{60}{Interval}$$

The formula is used to convert the meter values (in Wh) to the average power during the interval.

5. Charging stations

5.1. Phases rotation

The reference charging stations, as well as in the Flexpower, are coupled to the low voltage electrical grid via a three-phases connection.

In the reference stations configuration, the grid connection is limited to 25 A and each connector of the charging station is limited to 16 A. The control electronic allows the charging of the vehicle by closing the contactor associated to each connector. Between these two sockets, there is a phase rotation, allowing simultaneous charging of two single-phase vehicles with maximum power. The charging station is also able to detect if a single-phase vehicle is connected to the one connector and 2 phases on the other. In this case, the current is also limited as if two single phases vehicles were connected. The phases rotation is illustrated in Figure 3.

Consequently, for the reference stations, the maximum power available is 11 kW (230 V x 16 A x 3) if a single vehicle is connected and 8.6 kW (230 V x 12.5 A x 3) in case of dual occupancy.

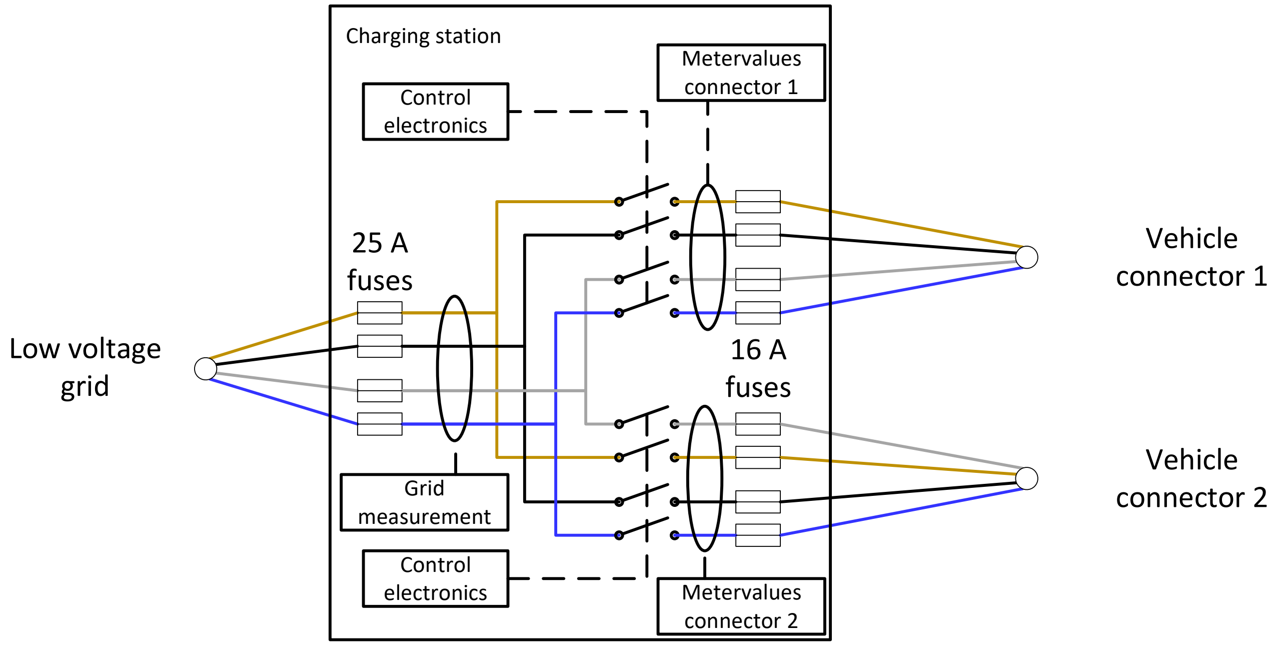

Figure 3: Protections and phases rotation for the reference charging stations. The wire's order is shifted between the connector 1 and 2.

In the Flexpower configuration, the phase rotation is the same, but the maximum protection current on the grid connection is upgraded to 35 A and each connector can deliver up to 32 A. The fuses are not present, and the current is monitored by the control electronics of the charging station. They are however drawn to illustrate the current limitations in the Figure 4.
With the Flexpower station, the maximum power available is 22 kW (230 V x 32 A x 3) if a single vehicle is connected and 11 kW (230 V x 16 A x 3) in case of dual occupancy. Thus, higher than for the reference station, if the connected vehicle can handle it.

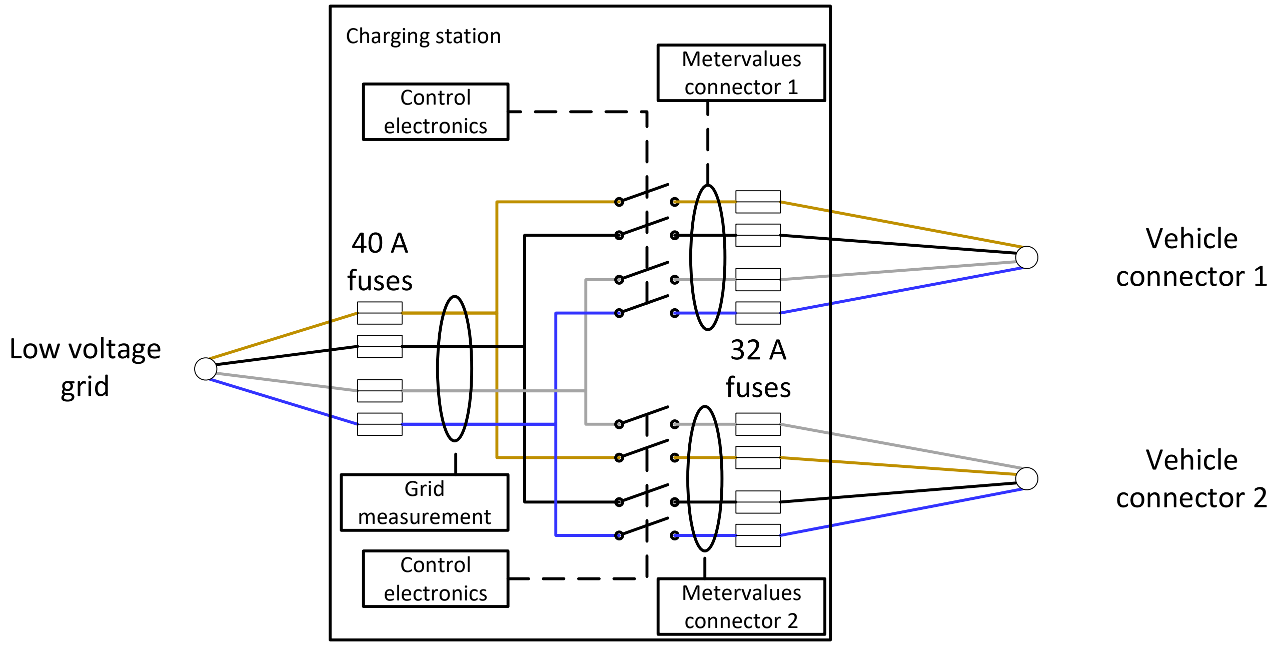

Figure 4: Protections and phases rotation for the Flexpower 1 charging stations

5.2. Share of power

The power or current share between the two sockets of the charging stations is made according to the "4 phases rules". If 4 or more phases are connected to the sockets, the current is shared. Otherwise the full current is available. Because the reference and flexpower limitations are different, they have their respective tables.

Table 6 and Table 7 provides respectively overviews of the different configurations reference and Flexpower poles. The voltage and current are considered nominal. The occupancy and vehicles phases configuration are considered to evaluate the current share and the related nominal power the vehicle can charge.

The grid columns show the power the network connection point delivers and the percentage of the maximum power it represents.

Table 6: Reference charging station current share between the sockets according to the number of phases connected. The 4 phases rules.

Profiles	Connectors							Grid	
	Occupancy		Sum phases	Current (A)		Power (kW)		Power (kW)	Load factor
	1	2		1	2	1	2		
Reference	1	Free	1	16	0	3.7	0	3.7	21%
	1	1	2	16	16	3.7	3.7	7.4	43%
	1	2	3	16	16	3.7	7.4	11.1	64%
	1	3	4	12.5	12.5	2.9	8.6	11.5	67%
	2	Free	2	16	0	7.4	0	7.4	43%
	2	2	4	12.5	12.5	5.8	5.8	11.6	67%
	2	3	5	12.5	12.5	5.8	8.6	14.4	83%
	3	Free	3	16	0	11	0	11	64%
	3	3	6	12.5	12.5	8.6	8.6	17.2	100%

Table 7: Flexpower charging station current share between the sockets according to the number of phases connected. The 4 phases rules.

Profiles	Connectors							Grid	
	Occupancy		Total phases	Current (A)		Power (kW)		Power (kW)	Load factor
	1	2		1	2	1	2		
Flexpower	1	Free	1	32	0	7.4	0	7.4	31%
	1	1	2	32	32	7.4	7.4	14.8	61%
	1	2	3	32	32	7.4	14.7	22.1	92%
	1	3	4	17.5	17.5	4	12.1	16.1	67%
	2	Free	2	32	0	14.7	0	14.7	61%
	2	2	4	17.5	17.5	8.1	8.1	16.2	67%
	2	3	5	17.5	17.5	8.1	12.1	20.2	84%
	3	Free	3	32	0	22.1	0	22.1	92%
	3	3	6	17.5	17.5	12.1	12.1	24.2	100%

From the Table 6 and Table 7, it is obvious that more power is available to the EV users with the Flexpower stations than the reference ones.

The tables can be used for researchers who are interested to know how a particular configuration of charging EVs will behave on public charging stations such as the reference stations and flexpower stations.

5.3. Alternating charging

On the Flexpower stations, the minimum current allowed during the peak hours is 8 A per phases in the case of a single occupancy. If more than 4 phases are connected to the charging station, the current is shared between the two sockets. The lowest current defined by the IEC 61851-1 is 6 A per phases. To be able to charge with 4 A, the charging station applies the alternating charging.

The current is kept to 8 A per phase for one socket, the second socket is put in idle, its current is set to 0 A. This setup is kept for 15 minutes. At the end of the interval, the socket configurations are switched, also for 15 minutes. The cycle continues until at least one vehicle doesn't charge anymore. Figure 5 illustrates the alternating charging.

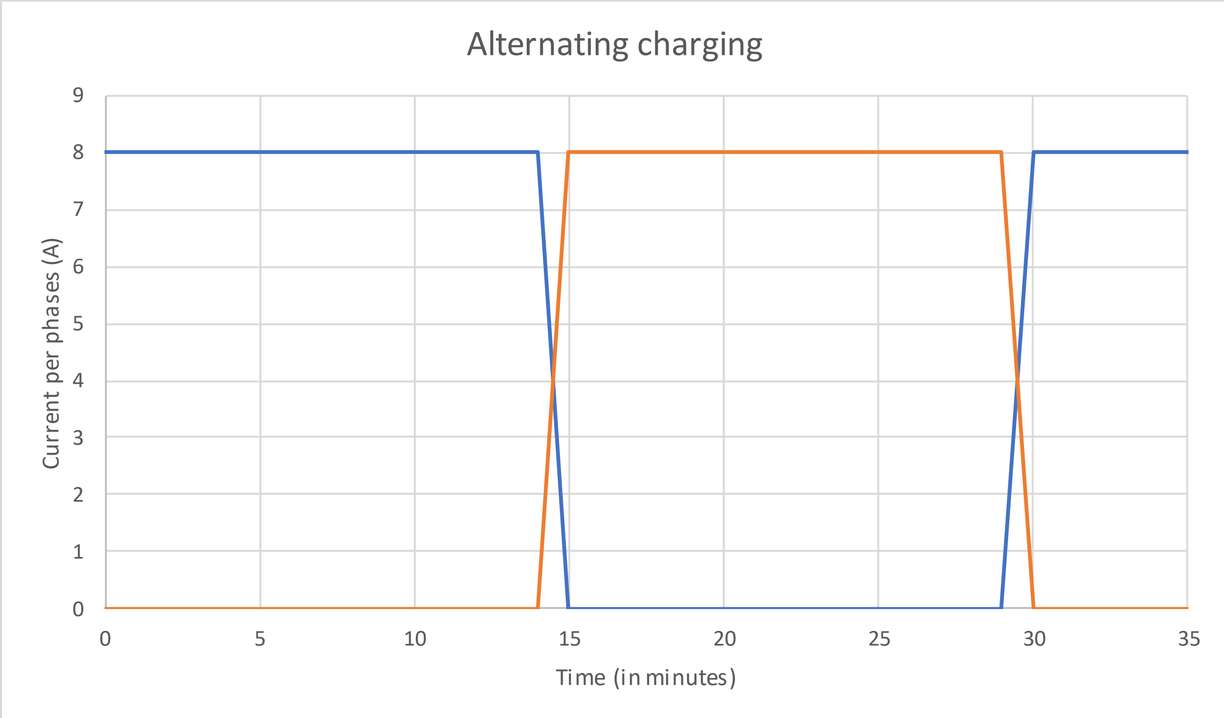

Figure 5: Illustration of the current swing during alternating charging.

This way, the average current charged by a vehicle a 4A even if the nominal current is 8A. During the experimentation, it has been found that some electric vehicles, were unable to exit the idle mode and restart the charge. Investigations shows that the norm was not always rigorously implemented.

Figure 6 shows an example of alternating charging. The blue line is the power limitation imposed by the profile. The sum of the charging power from the two sockets shouldn't be higher than this value. The green line is the power transferred to the vehicle connected to the first socket whereas the red one if for the second vehicle socket. The vertical dashed green and red lines are when the sockets 1 and 2 are suspended by the charging station. These lines occur every 15 minutes for both colours (30 minutes for each colour), illustrating the 15 minutes alternate charging. A few minutes after the SuspendedEVSE of the socket 1, the socket 2 starts to charge. The same process is to be seen with the socket 2 15 minutes later. The power doesn't reach 0 as the alternating commands aren't synchronised with the communication of the energy to the backend system.

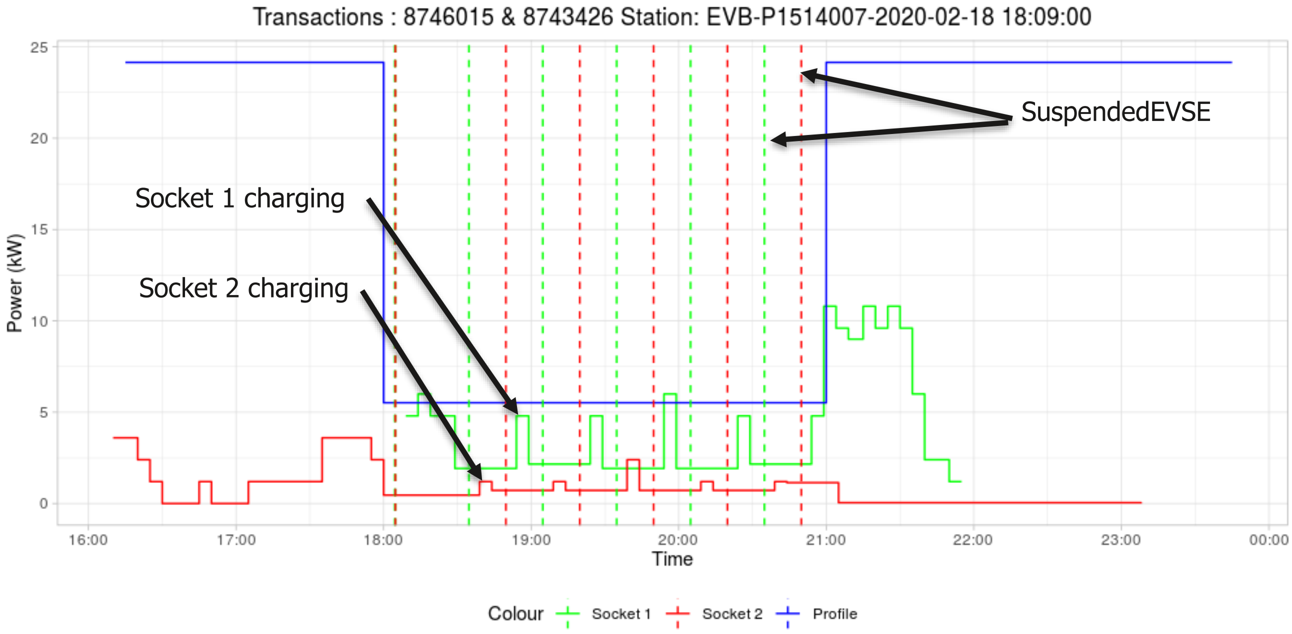

Figure 6: Example of alternating charge. Two vehicles are simultaneously connected to a charging pole. During the restricted period, the current values alternates between the two sockets. The value doesn't go down to 0 because the measured period is not synchronised with the actual current. The energy and thus the power are an average on the time interval.

6. Vehicles identifications

To evaluate the impact of the Flexpower on the various categories of vehicles, defined in Table 4, vehicles need to be identified based on the meter values data.

6.1. Flexpower and reference charging stations.

Both the Flexpower and reference charging stations can charge simultaneously two vehicles with 1, 2 or 3 phases. The main difference between both charging stations is the current delivered by the sockets.

Table 8: Nominal current delivered per phases on each socket.

	Reference	Flexpower
Single occupancy	16 A	32 A
Dual occupancy	12.5 A	17.5 A

6.2. General

The vehicles are identified according to the categorisation in Table 4.
For each interval of the meter values, the energy is converted in an average power (see 4.4). Then for each RFID, the maximum power is used to identify the vehicles. The relation between the maximum power and the categories is shown in the Table 9.

Table 9: Categorisation of the vehicles based on the maximum charged power

Maximum power	Vehicles
3.7 kW	1 phase - 16 A
7.4 kW	1 phase - 32 A or 2 phases - 16 A
11 kW	3 phases - 16 A
17 kW	3 phases - 32 A
22 kW	3 phases - 32 A

6.3. Focus on 7.4kW

Table 9 shows how the electric vehicles were categorised based on the number of phases and the nominal charging current. However, two types of vehicles, the 2 phases 16 A and the 1 phase 32 A are falling in the same power category, the 7.4 kW. A supplementary step is needed to separately identify them.
It is done by using the information from the reference station. As shown in the Table 8, the current in the reference stations is limited to 16 A per phase whereas the limit is set at 32 A on the Flexpower. A single phase 32 A vehicle will see the power limited at 3.7kW when charging on a reference station whereas the power remains the same for a 2x16 A vehicle. Thus, the vehicles identified as 7.4kW, but only charging at 3.7kW on the refence stations are 32 A single phase vehicles.

6.4. Classification result

From the method previously described, the data from the IDO-laad database (meter value and the CDR) are combined and treated to identify and qualify the vehicles. The result of this qualification is shown in Table 10. The 16 A vehicles, represents most of the vehicles, followed by the 1 phase 32 A and the 3 phases 25 A. Finally, the 3 phases 32 A vehicles are quite rare as they only represent 2% of the identified vehicles.

Table 10: Percentage categories for each vehicle

Categories	Nominal powers	Percentage sessions	Percentage vehicles	Percentage energy
1 phase - 16 A	3.7 kW	50%	44%	23%
1 phase - 32 A	7.4 kW	15%	13%	20%
2 phase - 16 A	7.4 kW	6%	6%	6%
3 phase - 16 A	11 kW	21%	28%	36%
3 phase - 25 A	17 kW	7%	6%	14%
3 phase - 32 A	22 kW	2%	5%	2%

6.5. Limit of the method

This method has some limitation:

- A 32 A vehicle only charging on a reference will be identified as a 16 A.
- If a 7.4 kW only uses the flexpower stations, it is identified as a 32A vehicles as the 2x16A are uncommon.

7. Resources

[1] IDO-laad (Intelligente Data-gedreven Optimalisatie Laadinfrastructuur) https://www.idolaad.nl
[2] https://www.netbeheernederland.nl/spanningskwaliteit/verdieping consulted the 16th of April 2020.
[3] https://ev-database.nl/ consulted the 16th of April 2020.