D. ELECTRIC VEHICLES MODELLING

Electrification of transport is under way. In Europe, plans are made for an exponential growth of electric cars, trucks, busses and light duty vehicles to charge from the grid. These will represent large amounts of additional electricity consumption.

First, it is important to recall that the assumptions are now detailed per segment: heavy duty freight (trucks), busses, light duty freight, and passenger cars (for Belgium a distinction in the amount is also made for private and company cars). The operating mode detailed in this appendix refers to the last two categories.

Linked to human behavior, the charging of electric vehicles (EV) can happen in different ways: from the natural charging profile, usually worsening the existing demand peak, to the perfect market dispatch of vehicle-to-grid, Elia models several ways cars could behave as the latter will impact adequacy, flexibility and the economic dispatch in the electricity market.

The methodology and nomenclature to model EVs is similar in most ways than since the previous AdeqFlex'23 study. **However, notable improvements are included for this AdeqFlex'25 study (further described later in this document):**

- Next to the home charging profile, **inclusion of work and public charging**, based on 2023 metered data, for the non-optimised profile (V0)
- Consideration of **regional tariffs and PV self-consumption** for locally optimised charging (V1H)
- Review of **EV availability** (i.e. connected to a charge point), based on 2023 metered data.

Just like in the previous edition AdeqFlex'23, EVs are modelled in different categories. The split is made between (i) cars able to have a bi-directional exchange of energy and those only able to charge from the grid (not injecting in the grid); (ii) cars following a pre-fixed time-series (out-of-market or not dependent on market conditions) and those following market dispatch of car charging, and; (iii) within the pre-fixed time-series, two profiles are considered, natural (charged when plugged-in) and optimised profiles .

This greater granularity represents more accurately the developments of EV charging making the modelling closer to realistic developments.

The market dispatch of EVs includes a limiting factor throughout the day linked to their availability and connection to the grid: an EV cannot be used for market dispatch if not connected to the grid. Additionally, the energy needs of EV owners is considered in the model: every day, a state of charge of EVs of 50% is guaranteed. This ensures to not model EV flexibility beyond what consumers would be ready to offer to the market.

The methodology now provides a more comprehensive picture of the analysis, allowing stakeholders to better understand the impact that EV have on the system and why it does. This appendix first explains the methodology to define the daily energy needs. Then an overview of the operation mode of electric cars considered in this study is given. After, the following sections detail each mode with their constraints and logic.

D.1. DEFINITION OF ENERGY NEEDS

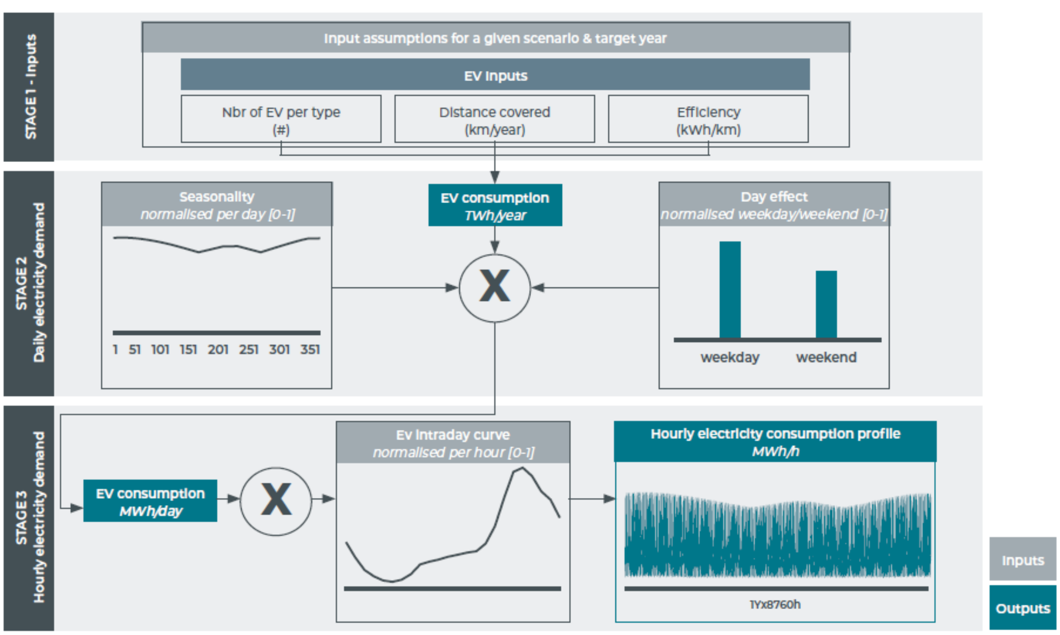
The construction of hourly profiles for electric transport consists of 3 main steps as shown in Figure D-1. This process is repeated for the different types of electric vehicles: passenger cars, light duty freight (vans), heavy duty freight (trucks) and buses. These are the types used for Belgium. Note that for other countries other types can be used depending on the data available in the PEMMDB or other databases, however, the methodology remains the same.

1. In a first phase the total annual electricity demand due to electric road transport is determined by the evolution of the number of electric vehicles, the assumed yearly driven amount of kilometers and the average yearly efficiency.

2. In a second phase this annual consumption is translated into daily electricity demand by using a seasonal scaling function (where charging is higher in winter due to lower battery efficiencies caused by colder temperatures) and by taking into account the difference between weekday/ weekend charging.

3. In the final step, the daily electricity demand for electric transport is translated into hourly electricity demand by using an intraday scaling profile. Those profiles depend on the flexibility assumed in the system, for which the methodology is explained in the following sections of this appendix.

FIGURE D-1 — CONSTRUCTION OF HOURLY ELECTRICITY DEMAND PROFILES FOR ELECTRIC VEHICLES



D.2. FLEXIBLE MODES OF OPERATION

Depending on the way Electric Vehicles (EV) are operated, their impact on the adequacy could vary. To represent best their possible impact on the system, Elia models different ways these can be operated and assume the proportion those modes would have in the scenarios (see Excel document with the scenario data).

Note that not all operation modes apply to different EV types. No flexibility are expected from trucks and buses: so only the Natural charging profiles are applied to them. But other EVs (passenger cars, light duty freight (vans)) can be split among the flexibility operation mode. An overview of the operation modes considered for EVs are summarised hereunder and in Table D-1.

	No Flex	Local Flex (H)	Market Flex (M)
Electric vehicles (passenger cars & LDVs)	Natural charging: Charging your car regardless of financial incentives	Optimised at Home: Minimise your costs following regional tariffs, or maximise PV self-consumption	Optimised in the Market: Minimise your costs following market signal based on merit-order dispatch
Rationale	V0 EV charging when plugged	V1H EV load locally optimised V2H EV to home (bi-direction)	V1M EV load optimised by the market V2M EV to market (bi-direction)
Modelling	Pre-defined time series	Pre-defined time series	Dispatched by the model following energy and power constraints

Table D-1: List of the operation modes considered for electric vehicles

An EV can thus be operated in the following ways:

V0: No optimisation

- Natural Charging (V0): here, a pre-fixed time-series is inputted in the model as load. The charging happens as soon as the EV is connected to a charger. In the previous edition of the study, only home charging was considered. One improvement of the next AdeqFlex'25 study, is to integrate profiles for work and public charging based on 2023 metered data. The three profiles are combined in different proportions through the time horizon of the study, giving an aggregate profile that is not optimised.

V1: one-direction optimised charging

- **Local charging (V1H):** just like V0, this is a pre-fixed load time-series. This profile corresponds to an optimisation based on a local signal (in opposite to a centralised market signal). This signal could be grid tariff (capacity, time of use), or incentivised PV self-consumption. For the next AdeqFlex'25 study, this profile has been improved to consider PV self-consumption and regional tariffs. Indeed, tariff differs in regions: there is a capacity tariff in Flanders (which aims to minimize peak) since 2023, and time of use tariff in Wallonia (incentivizes consumption in certain periods of the day) expected by 2026. More details are given in the associated section of this appendix.
- **Smart charging (V1M):** the best case for adequacy, would be to dispatch EV charging when prices are low. In this operation mode, the model dispatches the load every day, to

minimise the operation cost of the market, thus minimising the price at which the car is charged. This operation mode follows power constraints through the day mimicking that not all cars are connected through the day. For the next Adeqflex'25 study, this has been reviewed based on 2023 metered data. It is important that several barriers such as market developments or smart charging infrastructure need to be lifted to allow such optimisation.

V2: bi-directional optimised charging/ discharging

First it is important to remind the reader that to perform bi-directional charging, both the car and/or the adequate charging infrastructure should be developed.

- **Vehicle-to-home (V2H):** Like V0 and V1H, this corresponds to a pre-fixed time-series of load. This technology refers to the ability of electric vehicles to supply power to homes. With the right regulatory framework, consumers could be incentivised to charge when the load is usually the lowest, and use their charged EV as a power source for their homes. This mode of operation assumes a round-trip efficiency of 80% [IEE-1]. For the next AdeqFlex'25 study, this profile has been improved to consider PV self-consumption and regional tariffs, just like V1H.
- **Vehicle-to-market (V2M):** better known as vehicle-to-grid or V2G, this corresponds to using a fleet of EVs as a battery. Provided with the right market incentive and infrastructure, aggregators could access market data as well as charger's data to dispatch the EV to charge or inject power to the grid to react to market prices or to the balancing market. In this operation mode, the model dispatches the charging and the injection in order to minimise the system cost, and hence the electricity price. Just like V2H, this mode of operation takes into account a round-trip efficiency of 80% [IEE-1]. Similarly, the power constraints (i.e. how many cars are connected to a charger) through the day has been reviewed for the next AdeqFlex'25 based on 2023 metered data.

Furthermore, bear in mind that it is likely that not the whole EV fleet will follow one operation mode. It is likely that in the future, a share of the EV fleet will follow one or the other operation mode. The assumptions taken for each segment are detailed in the excel accompanying public consultation.

D.2.1. V0 - NATURAL CHARGING

This operation mode mimics charging as soon as the EV is plugged in. This profile is an aggregation of three locations where EV owners can charge: home, work and public charging stations. For each of these location, a daily profile is considered. The new profiles (compared to previous AdeqFlex'23 study) of work and public charging were developed based on 2023 metered data. The process is displayed on figure D-2: Each of the 3 profiles are displayed at the top of the figure. These profiles need to be combined in different proportions to make an aggregate profile for EVs following the V0 operation mode. These proportions are scenario dependent (% of the energy need charged at home, % charging at work, % charging in public places), but an illustrative example is given in the middle of the figure. Finally, considering these shares, an aggregate V0 load profile is displayed at the bottom. This profile represents the percentage of the daily load at each hour for an EV charging.

In this example, the reader can see that little charging happens during the night while two peaks can be distinguished: one in the morning and one in the evening. The morning peak is linked to the work and public charging profile (people leaving their home in the morning and charging at work or in public places). Whereas the evening peak comes from home charging (people going back to their home at the end of the day and charging at home). The proportion of each peak changes depending on the share considered for the three profiles (home, work and public) together.

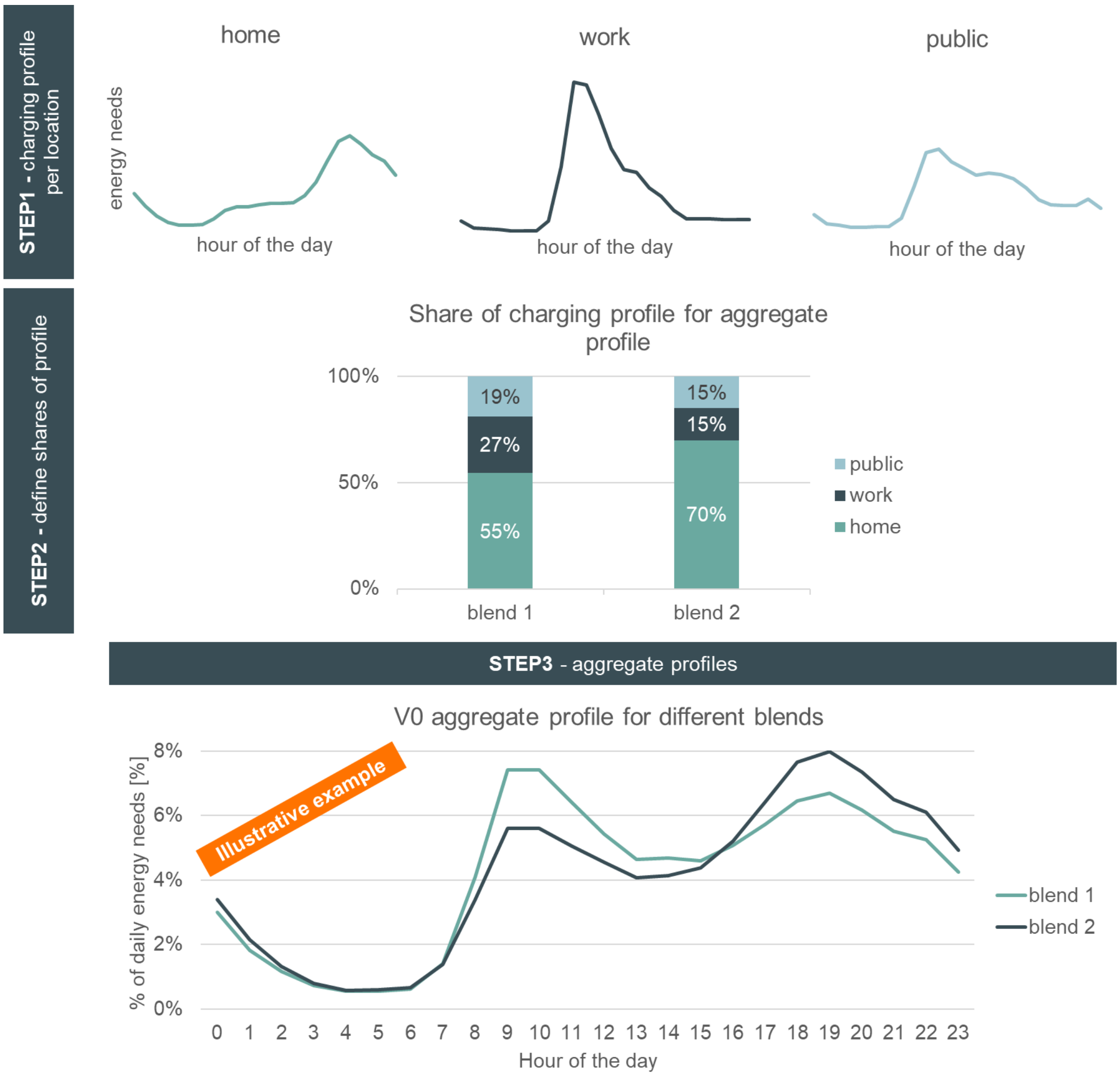


Figure D-2: Illustrative profile for the construction of the V0 aggregate profile, based on individual profiles of home, work & public charging.

D.2.2. V1H - LOCAL CHARGING

Charging the EV during the peak is not ideal for grid management. Different local signals (in opposition to market signals), exist to incentivise EV owners to charge at a different moment.

For the next AdeqFlex'25 study, major improvements have been included in the study for the V1H profile. Notably, the profile now considers regional differences in Belgium both in terms of (i) tariff and (ii) PV self-consumption.

Regarding the first improvements, it is known that regional tariffs are either already existing or planned to be implemented in Belgium. In 2023 the capacity tariff started in Flanders[1], and a time-of-use tariff is expected in Wallonia by 2026[2]. In a nutshell, the capacity tariff in Flanders incentivise to minimise the peak load (by increasing your bill based on average monthly peak). And the time-of-use tariff in Wallonia defines 3 levels of prices for different periods of the day (the most expensive one being from 5 PM to 10 PM).

These two tariffs will impact the way people charge their cars, giving them incentives to charge in a way that is best for the grid (i.e.: minimising peak, or outside peak hours). However, both tariffs will not impact charging behaviour in the same way. For this reason, the next AdeqFlex'25 study includes profiles for each tariffs / region.

These profiles are developed by minimising the consumer bill. This assuming that consumers have no dynamic contracts, and hence that the only two variable elements of the bill are the tariffs, and PV production.

Starting from a synthethic load profile (representative of a residential load curve or a user across Belgium) from Synergrid[3], an algorithm dispatched the energy demand of the EV as to minimise cost (considering energy costs as well as an estimate of tariff costs).

Also, the locally optimised profile now considers PV self-consumption. With greater and greater PV penetration in the residential and tertiary sector, it is expected to have flexible electrified assets (like EV) integrate renewable energy directly where it is produced. These profiles then consider the assumed local PV production (the weather-dependent production is considered by taking into account the climate years used in the study).

Hence, there are different profiles for the region of Flanders and Wallonia, and this profile differs for each day of each climate year. An illustrative example for a day in winter, with PV self-consumption is given on figure D-3. The figure depicts averaged EV profile for each region, in winter, with and without PV self-consumption.

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[1] The capacity tariff | Flanders.be

[2] Méthodologie tarifaire 2025-2029 | CWAPE

[3] Profils de charge synthétiques - Profils de production synthétiques - Profils de charge réels - Synergrid

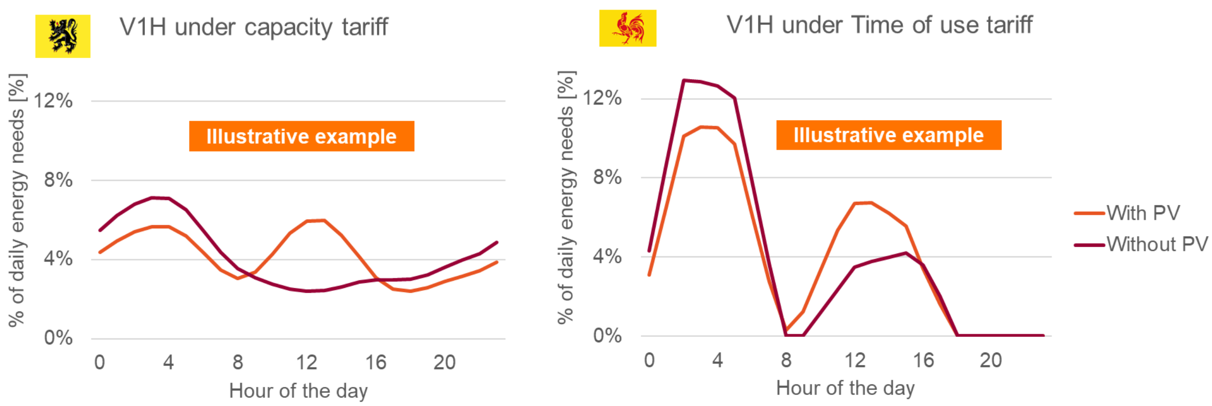

Figure D-3: illustrative examples of local charging profile (V1H) for two different tariffs (capacity tariff, and time of use tariff), with and without PV production.

Following the modelling, under capacity tariff, charging is incentivised to be spread throughout the day as to minimise peak. Whereas under time of use tariff, the charging occurs in periods where the tariff costs are the lowest (i.e. mostly during the night and also during working hours) and is cut to 0 when tariff costs are the highest (i.e. during the morning and evening peaks). Also, when PV production is included, PV self-consumption is prioritised (higher consumption during the day when sun is shining).

Note that both representations result from a modelling exercise, based on available information of the tariff at the time of writing this methodology (e.g. future tariff costs are still unknown). The objective of this exercise is to anticipate future behaviour of EV charging that are incentivised by different tariff structures.

D.2.3. V1M –SMART CHARGING

Ideally for both the grid and the consumer, the EVs would be charged at times where prices are the lowest. Consumers could be financially incentivised to do so, or chargers would automatically choose the best moment to charge depending on prices. This behavior is mimicked by the V1M operation mode. Here, the model dispatches the load according to the market needs, which are different for every day and depending on the weather. The dispatch occurs within given power and energy constraints.

The first constraint concerns the power rate at which the load can be charged. This is defined by the number of cars connected to chargers, which is not the same throughout the day. This is called here the V1M availability. The V1M availability is first defined for every day as a share of EVs connected to the grid for each hour of the day. Details of this availability is given on Figure D-4. For the next Adeqflex'25 study, this availability has been reviewed based on 2023 metered data, to account for charging at work (which increases connection of cars during the day). Note that it is assumed that EV charging in public places do not offer flexibility (therefore no V1M/V2M assumed there).

To set a constraint on power, there is a need to go from a percentage to an energy consumption per hour. For this purpose, one starts with the number of EVs which will follow this operation mode by multiplying the number of EVs in the total fleet and the share of EVs defined to be optimised a

V1M. This is then multiplied by the power of a charger (the assumption is taken that this corresponds to a value of 7kW for residential and work chargers), giving a maximum charging power for V1M, which is applied on the V1M availability profile. This results in an upper boundary for the charging of EVs.

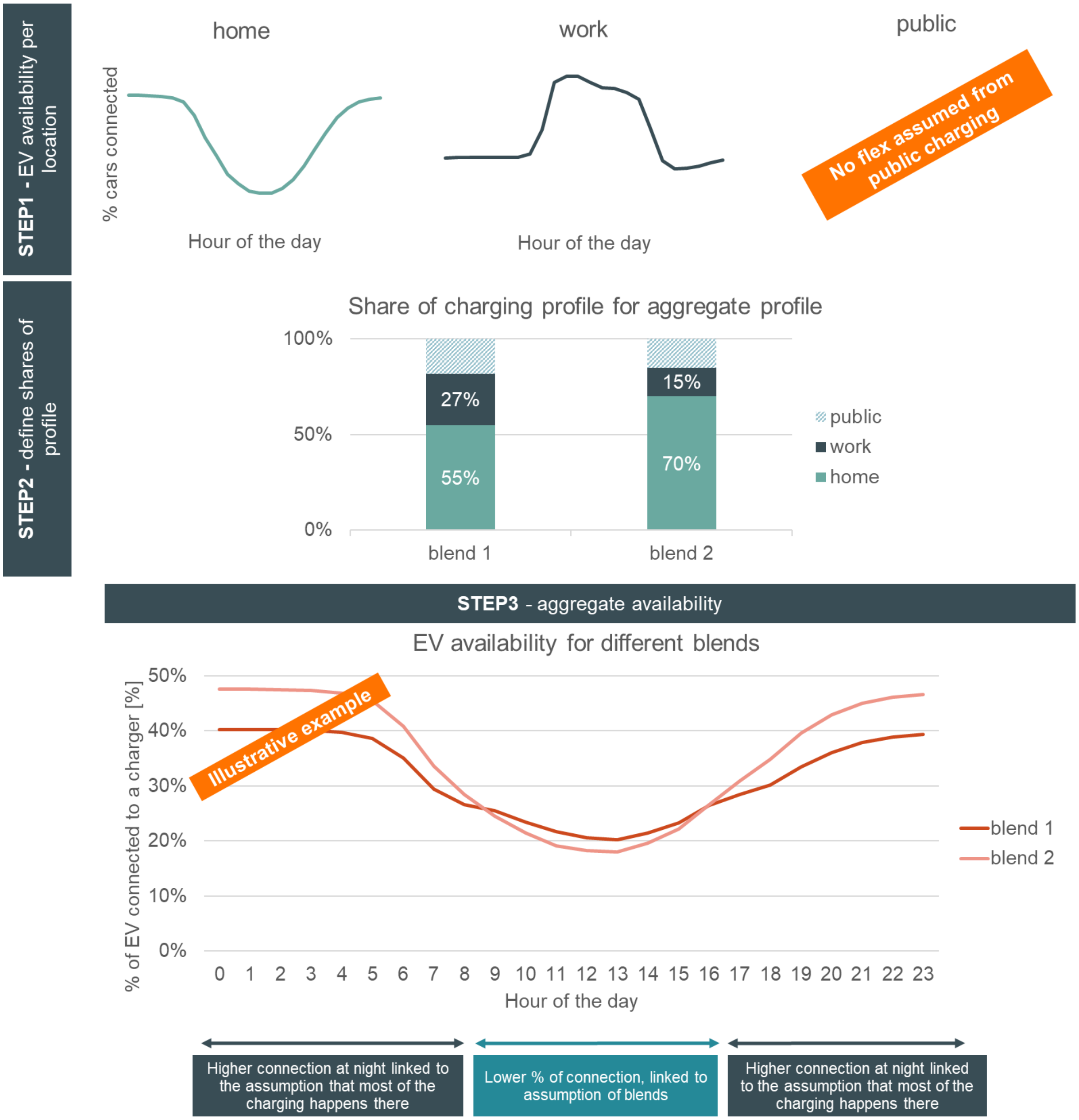

Figure D-4: Availability (i.e. connection to a chargepoint) of EVs through the day.

The second constraint enforces the amount of energy that must be charged every day. This results from multiplying the average efficiency [kWh/km] of cars and the distance that these need to cover every day.

In conclusion, a given amount of energy needs to be charged every day, and the model dispatches this load through the day, given limits on power rate, at the moment where load and electricity prices are the lowest. Due to the variability across 'Monte Carlo' simulations, the dispatch of V1M can be highly variable. However, trends can be identified across simulations when looking at different metrics. Notably (i) the average and (ii) the range between the percentile 10th (P10) and percentile 90th (P90) of the intra-day dispatch profile across 'Monte Carlo' years. These percentiles represent the value below which 10 (respectively 90) percent of the observations or data points in a distribution fall.

An illustrative example is given based on results of Adeqflex'23 in figure D-5. These trends for summer and winter are displayed at the bottom of Figure D-5. During these two seasons, the residual load through the day is not the same due to the seasonality of load, and the daily variations of RES (i.e. solar generation is greater around noon). In summer, most of the charging takes place during the day when solar panels are usually producing more). Whereas in winter, charging happens outside
peak hours (i.e., morning peak at 8 AM and evening peak at 8 PM). Note that the charging is indeed limited by the V1M availability around midday (during solar generation).

FIGURE D-5 — OVERVIEW OF THE METHODOLOGY TO MODEL SMART-CHARGING (V1M) AND RESULTING PROFILES FROM HOURLY MARKET SIMULATIONS

D.2.4. V2H – VEHICLE-TO-HOME

In the coming years, it is expected that the penetration of bi-directional power chargers and cars able to handle it will increase. Indeed, several car manufacturers are developing chargers and cars that will have the technical possibility to charge as well as inject back power to the network. With proper market reforms, behavior virtuous for the grid can be incentivised such as netting its local house load, or consumer allowing aggregators to use their EVs as virtual power plants.

Those could be used to charge when the prices are the cheapest or to provide ancillary services to the system. This section focuses on the former case: smarter management of an EV charging and injection to reduce peak load and reduce consumption based on network tariffs.

The V2H profiles have been developed according to the same methodology as explained in V1H. Hence, the profiles differ for each region, each day of each climate year (when integrating PV self-consumption). Illustrative examples for winter are given in Figure D-6, with and without PV self-consumption for V2H. This profile answers the same energy needs than V0, considering a roundtrip efficiency of 80% [IEE-1].

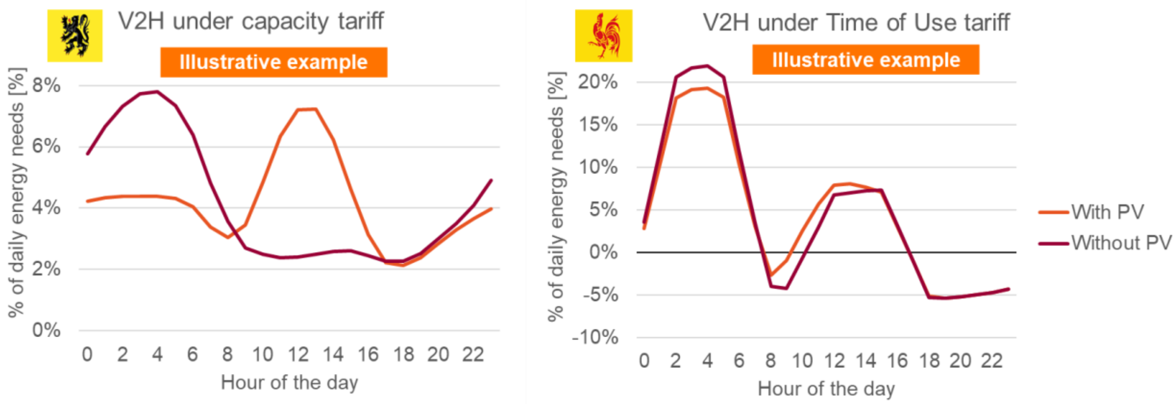

Figure D-6: illustrative examples of V2H profiles averaged over winter

The reader can note that in Flanders, charging is spread as to minimize peak. With current information in the model, injection in the grid is not incentivised due to round-trip efficiency that would increase consumption at another time. However for Wallonia, the time of use tariff has such large difference in costs in the different periods of the day, that injection is incentivised during morning and evening peak.

D.2.5. V2M – VEHICLE-TO-MARKET (VEHICLE-TO-GRID)

As explained in the last section, thanks to technological developments, EVs will have the possibility to inject electricity back to the grid with a round-trip efficiency of 80% [IEE-1]. With the proper market reforms, this exchange of energy could be optimised following market needs. Or in other words, EVs could be aggregated to work as coordinated battery storage to balance production and load. This behavior is mimicked in V2M. The dispatch occurs within given power and energy constraints. The methodology to build these constraints is summarised in Figure D-8. The reader should note that this figure is based on simulation results from Adeqflex'23, but are still relevant as illustrative purpose of the methodology.

Regarding the constraint, the logic is the same as for V1M. The first constraint concerns the power rate at which the load can be charged. This is defined by the number of cars connected to chargers, which is not the same throughout the day. Elia calls this the V2M availability. The V2M availability is first defined for every day as a share of EVs connected to the grid for each hour of the day. Details of this availability are given in Figure D-4. To set a constraint on power, there is a need to go from a percentage to a consumption. For this purpose, one starts with the number of EVs which will follow this operation mode by multiplying the number of EVs in the total fleet and the share of EVs defined as following V2M. This is then multiplied by the power of a charger (this value is assumed to be of 7kW for most residential chargers), giving a maximum charging power for V2M, which is applied on the V2M availability profile. This results in an upper boundary for the charging of EVs.

The second constraint enforces the amount of energy that has to be charged every day. This results from multiplying the average efficiency [kWh/km] of cars and the distance that these need to cover every day. In conclusion, a given amount of energy needs to be charged every day, and the model dispatches this load through the day, given limits on power rate, at the moment where load and electricity prices are the lowest. Due to the variability across hourly market 'Monte Carlo' simulations, the dispatch of V2M can be highly variable. However, trends can be identified across simulations when looking at different metrics. These will be identified after results of the simulation in the next Adeqflex'25 study.

FIGURE D-8 — OVERVIEW OF THE METHODOLOGY TO MODEL VEHICLE-TO-MARKET (V2M) AND RESULTING PROFILES FROM HOURLY MARKET SIMULATIONS