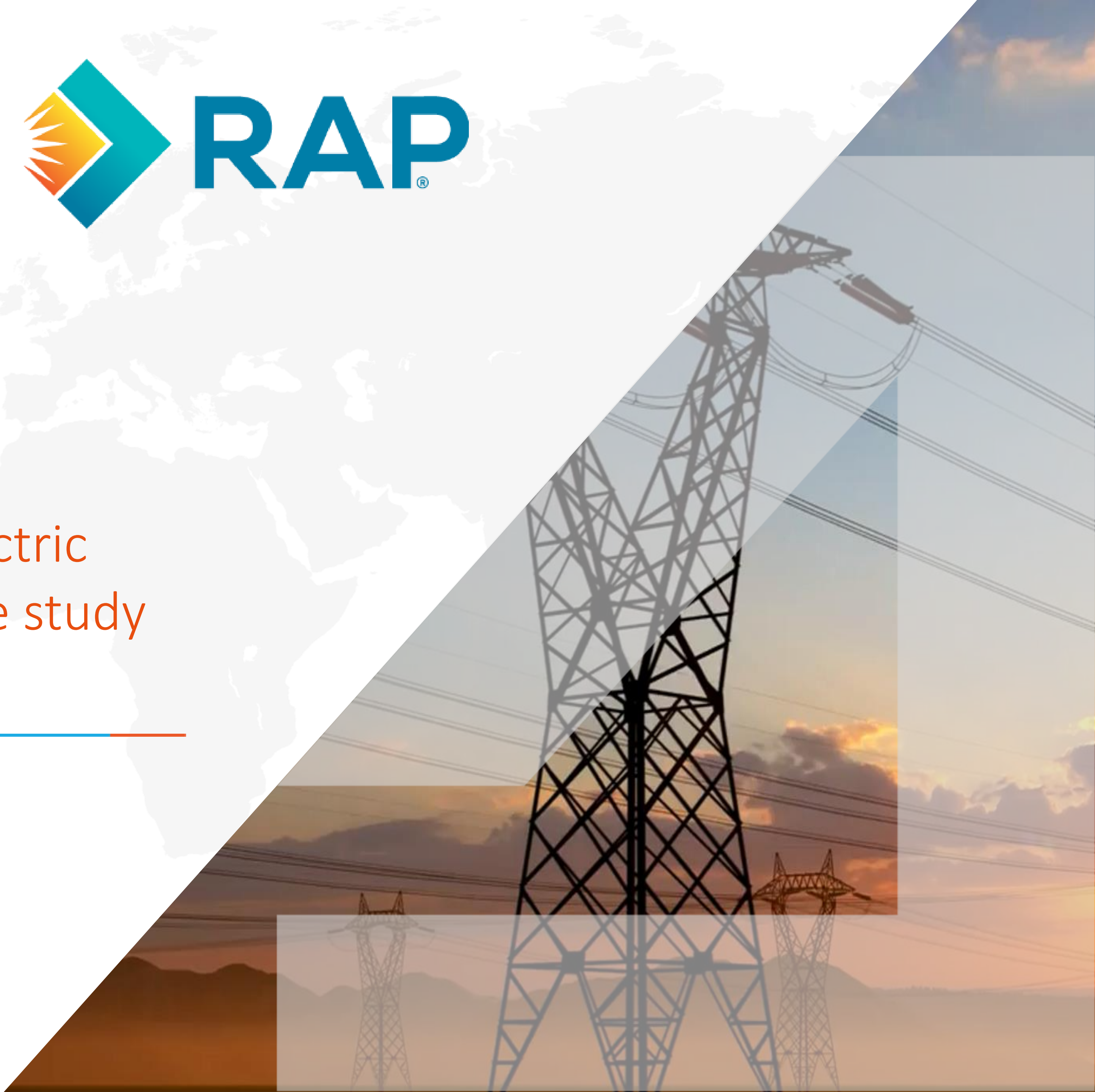
Savings from smart charging electric cars and trucks in Europe: A case study for France in 2040

Technical Report



Paris

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www.artelys.com

Introduction

- The aim of this study is to quantify the savings generated by the smart charging of electric vehicles on the reinforcement of the electricity distribution network by 2040, in the European context.

- The analysis is based on a physical simulation of the medium voltage electrical distribution network, coupled with demand evolution hypotheses for two smart charging deployment scenarios. The study focuses on a selected French area chosen for its typical profile, representing an average and heterogenous region, with both rural and dense urban areas.

- This document outlines the assumptions made for conducting simulations on the electricity distribution network and details the methodology used. It then presents the results of the main study and the sensitivity analysis on V2G.

Table of content

Methodology and assumptions

Overall methodology

The methodology used in this study follows these steps :

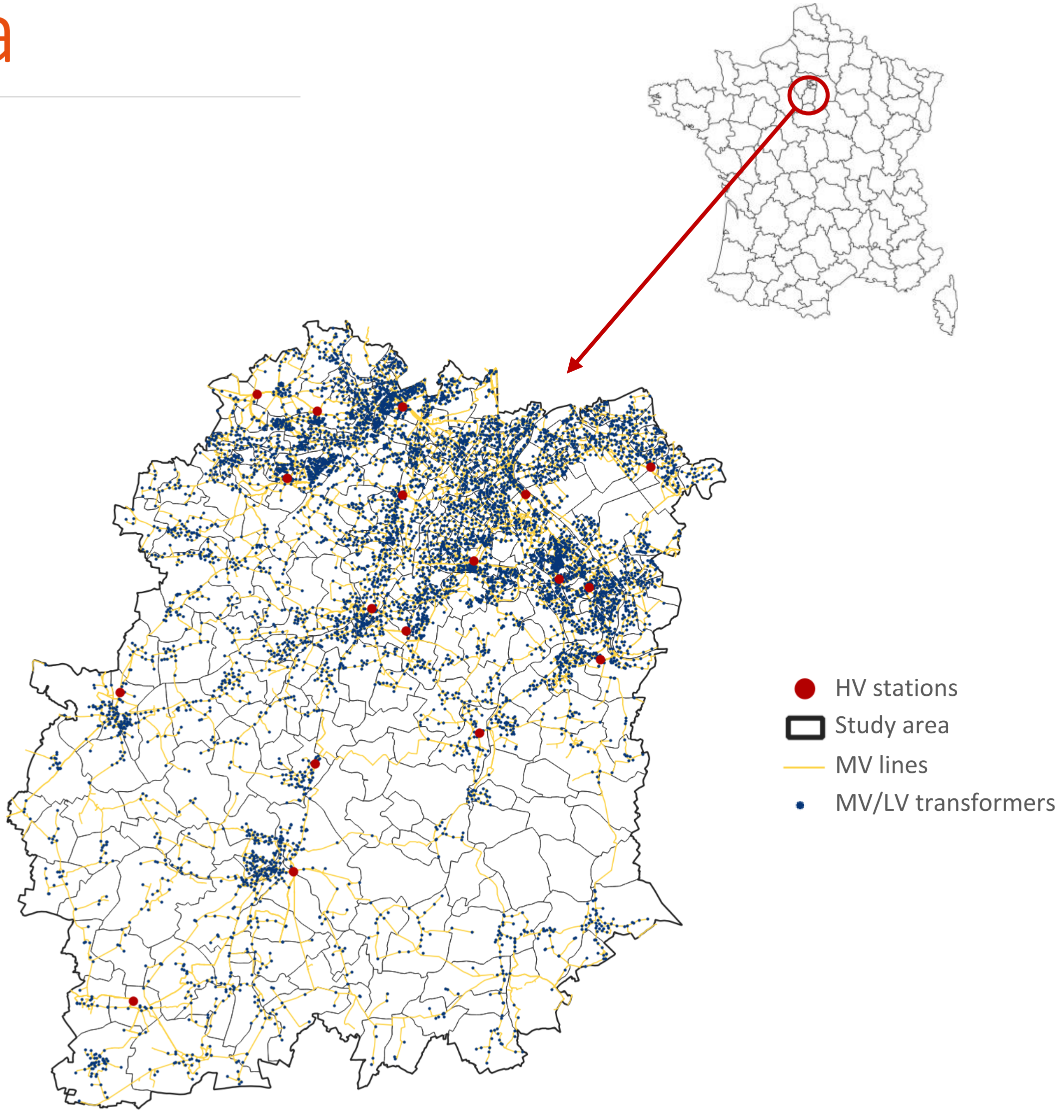
1. **Physical modeling of the MV network for a study area.** The modeling includes MV lines, MV/LV substations and HV/MV substations.
2. **Projection of the baseload to 2040.**
3. **EV modeling.**
4. **Construction of EV load curves for two scenarios of flexibility.** The comparison between scenarios allows to estimate the marginal impact of smart charging.
5. **Power flow simulations of the MV network.** Simulations are performed in the 2022 situation and the two scenarios.
6. **Calculation of grid reinforcement needs and related costs** for both scenarios.
7. **Sensitivity analysis to evaluate the impact of V2G.**

Methodology and assumptions

1. Physical modeling of the MV network

Study area

- Chosen Area : 1800 km², 1.3 million people.
- 507 IRIS[1] meshes
- Modeling of the **medium voltage distribution grid** operated by ENEDIS[2].
- Distribution grid **characteristics :**
  - **Medium voltage (HTA)** : 415 km overhead lines and 4,572 km of underground lines.
  - 18 HV stations and 7,196 MV/LV transformers.



Medium-voltage network layout of the study area

[1] In French, IRIS states for "*aggregated units for statistical information*" , it is a statistical division of the territory, defined to include around 2000 inhabitants per unit.
[2] Part of the rural territory is operated by a local network operator, representing 2.3% of the total population.

Methodology and assumptions

2. Projection of the baseload to 2040

Baseload assumptions (excl. EVs)

- 2022 consumption and production by IRIS and sector is made available in open-data by ENEDIS.
  - The consumption baseload is then reconstituted based on 27 profiles (25 for consumption and 2 for production).
- 2040 consumption is projected based on the French TSO’s “Energy pathways to 2050” study (2022).
  - The scenario “electrification +” is selected as it is the new reference pathway according to RTE in 2023.
  - This projection is based on the National low carbon strategy (2020).
- The diffuse solar PV production is projected based on the National energy-climate strategy (2023).
  - PV production is spread throughout the area according to available roof surfaces. Installed rooftop capacity in 2040 is estimated at **600 MWp** (based on *RTE Energy Pathways to 2050* assumptions : 1,5 GWp in the area of which 40% is rooftop PV).
  - Centralized generation (PV and wind) is not projected. Indeed, unlike centralized generation, diffuse generation creates uniform pressure on the grid, which tends to affect (upwards or downwards) the capacity margin of substations. Besides, centralized power plant often involve specific reinforcements borne by the project developers.

Sector	Evolution by 2040
Residential	-10%
Tertiary	-5%
Industry	+30%
Agriculture	-5%

Assumptions used for the evolution of the baseload

Methodology and assumptions

3. EV modeling

EV fleets

- Eight different fleets are considered. Four of them are manageable.
  - Each of the fleets is defined by a charging type, a volume of energy, an average charging power level and specific arrivals and departures curves.
  - For the manageable fleets, two types of load curves are computed : one uncontrolled and one controlled.

Name	Type of EV	Charging type	Manageability
EV1	eLDV	Home	Yes
EV2		Work	Yes
EV3		Public normal	Yes
EV4		Public fast	No
EV5		Highway fast/ultrafast	No
EV6	eHDV	Depots	Yes
EV7		Warehouses	No
EV8		Public fast/ultrafast (incl. Highways)	No

EV consumptions

- Each fleet is associated to an annual energy demand.
  - Values are provided by the ICCT based on the **CO2-standards aligned scenario.**

Name	Type of EV	Charging type	Annual Demand (GWh)	Share of the total EV demand
EV1	eLDV	Home	1 184	50%
EV2		Work	191	8%
EV3		Public normal	339	14%
EV4		Public fast	173	7%
EV5		Highway fast / ultrafast	97	4%
EV6	eHDV	Depot	290	12%
EV7		Warehouses	5	0,2%
EV8		Public fast/ultrafast (incl. Highways)	96	4%
Total			**2 375**	**100%**

Charging power level

- Each fleet is associated to an average charging power level.
  - Values are provided by the ICCT.

Name	Type of EV	Charging type	Average charging power level (kW)
EV1	eLDV	Home	5.15
EV2		Work	16.83
EV3		Public normal	12.6
EV4		Public fast	71.25
EV5		Highway fast / ultrafast	163.75
EV6	eHDV	Depots	31.2
EV7		Warehouses	125
EV8		Public fast/ultrafast (incl. Highways)	450

Methodology and assumptions

4. EV load curves

EV load curves : methodology

Below are the different steps in the construction of electric vehicle load curves, which are detailed in the following slides :

1. A tariff curve reflecting the national net power demand is built in order to drive the smart charging.
2. Load curves are generated based on an hourly-based optimization resolution combining arrivals and departures curves and the tariff curve.
3. Manageable fleets admits two types of load curves : one uncontrolled and one smart.
4. Two flexibility scenarios are defined by a rate of smart charging in the demand of manageable fleets.
5. Power demand for each fleet is distributed across the iris zones according to allocation keys.

Tariff curve - motivations

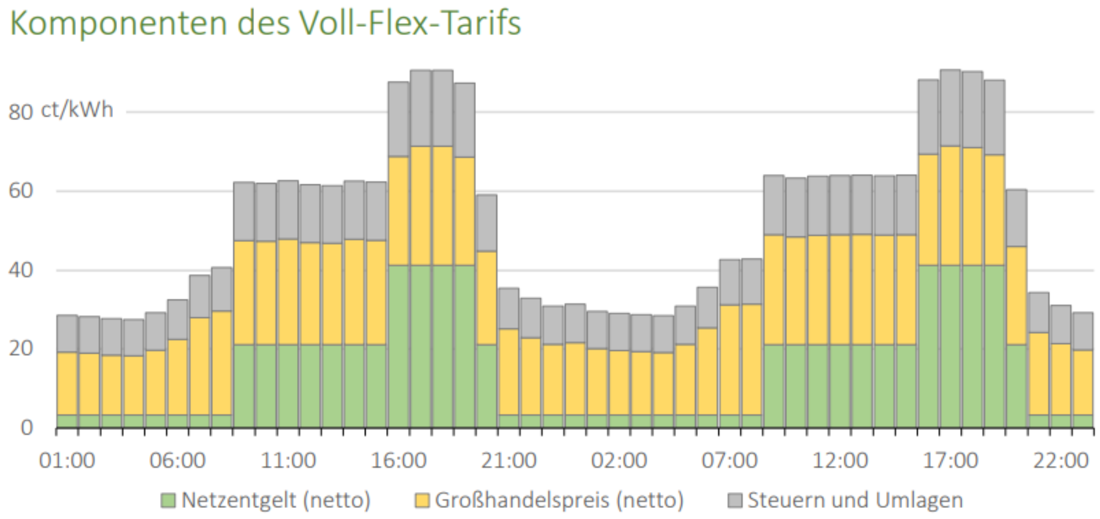
- Electric Vehicles that are able to perform smart charging are optimizing their charging in regard of the electricity price within their flexibility window. Hence, the shape of the electricity tariff curve has a major impact on the result of the optimization.

- The tariff curve has to be aligned with the state of the electricity production, and be consistent with observed consumption peaks : A Time of Use tariff allows higher prices during high demand hours, and incentive prices during low demand hours. Thus, vehicles are expected to prefer charging during periods of reduced overall electricity demand.

- The construction of the tariff curve is described below.

Tariff curve - principles

- Inspired by the *voll-flex* tariffs[1], an electricity tariff with two components is proposed :
  - An **Energy price-based** component, built from actual day-ahead prices.
  - A **Time-of-Use (ToU) component**, built in order to incite consumption out of grid peak time and during solar photovoltaics production.
- This tariff curve will define the price of the electricity consumed by all EV fleets. Smart charging vehicles will plan their charging times in regard of this curve.

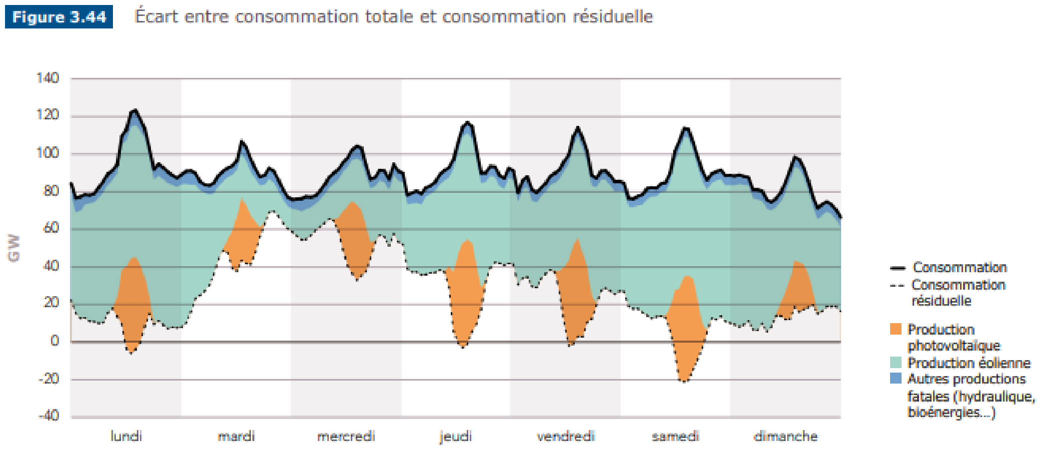


Example of a fully flexible tariff with a ToU tariff (green) and an energy price based component (yellow)[1].

[1] Added value of decentralized flexibility, Neon energy, [link]

Tariff curve - assumptions

- Current French ToU tariffs propose a two-levels shape, with peak hours from 7:00 to 22:00.
- Based on French TSO's *RTE Energy Pathways to 2050* projection, important PV production peak are expected during the daytime by 2040 (even in winter). Hence, a two-peaks ToU curve is built, with lower prices during PV production.

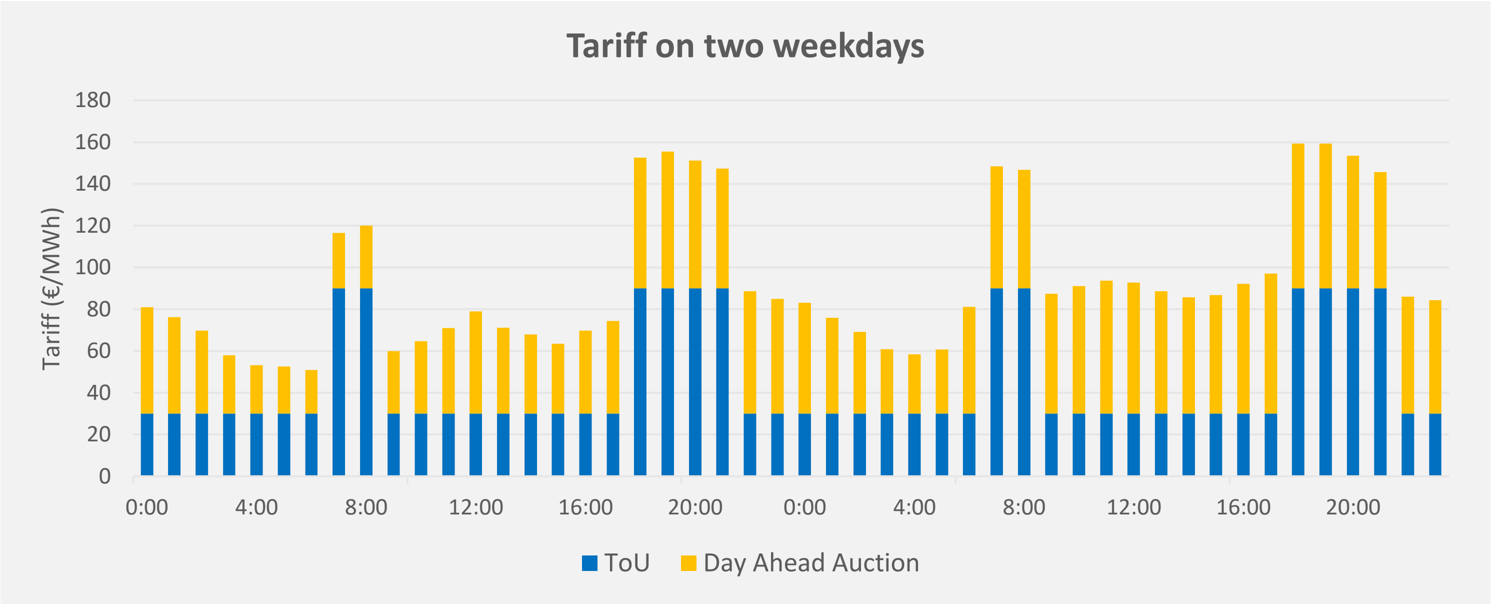


Consumption and RES production, winter week, 2050[1]

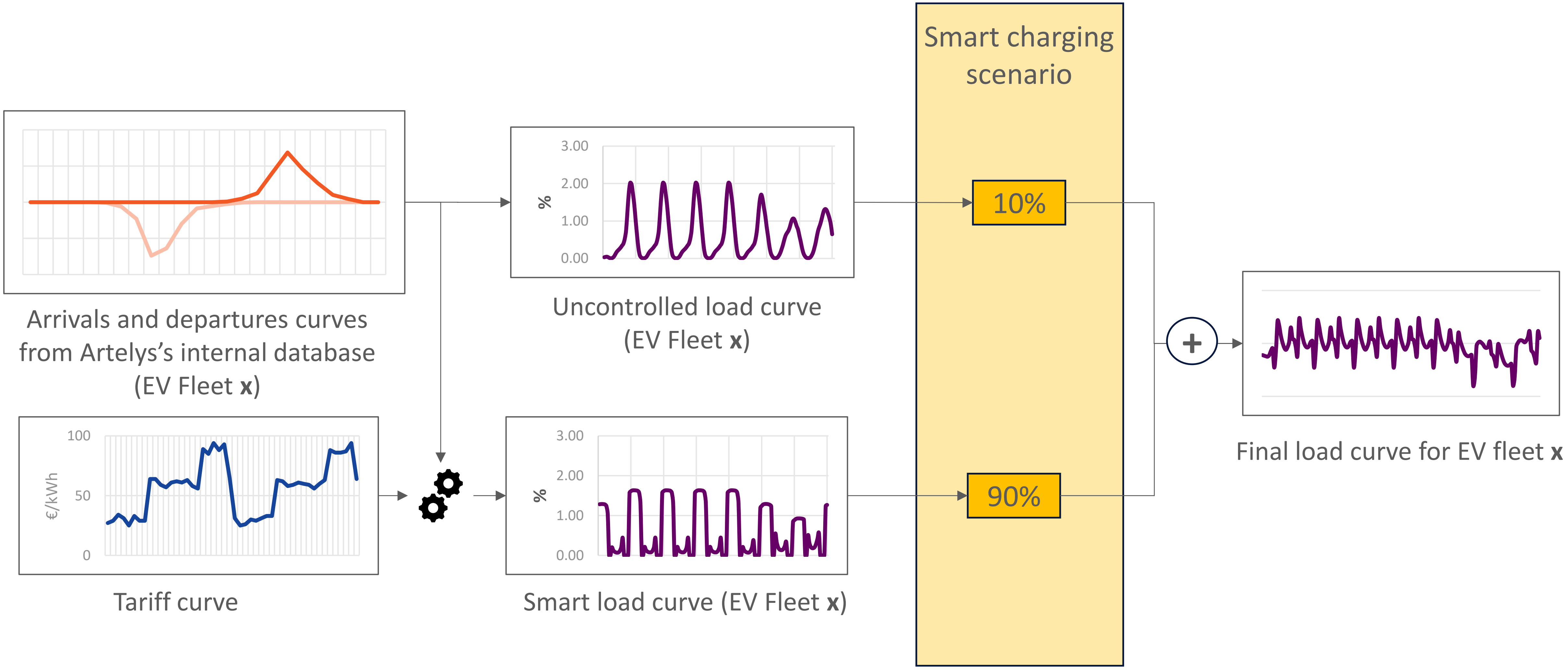
[1] Energy pathways to 2050, RTE, [link]

Tariff curve – shape and tariff

- Based on internal net demand projections for 2040, two price peaks have been identified : 7:00 → 9:00 and 18:00 → 22:00. They only occur on weekdays.
- The ToU component is built to match the *TURPE* (French network usage tariff) price for an average consumer.
- The energy-price based component is built from 2019 French day-ahead prices.



Load curve building methodology



Note : Curves are shown for illustrative purposes only.

Smart charging scenarios

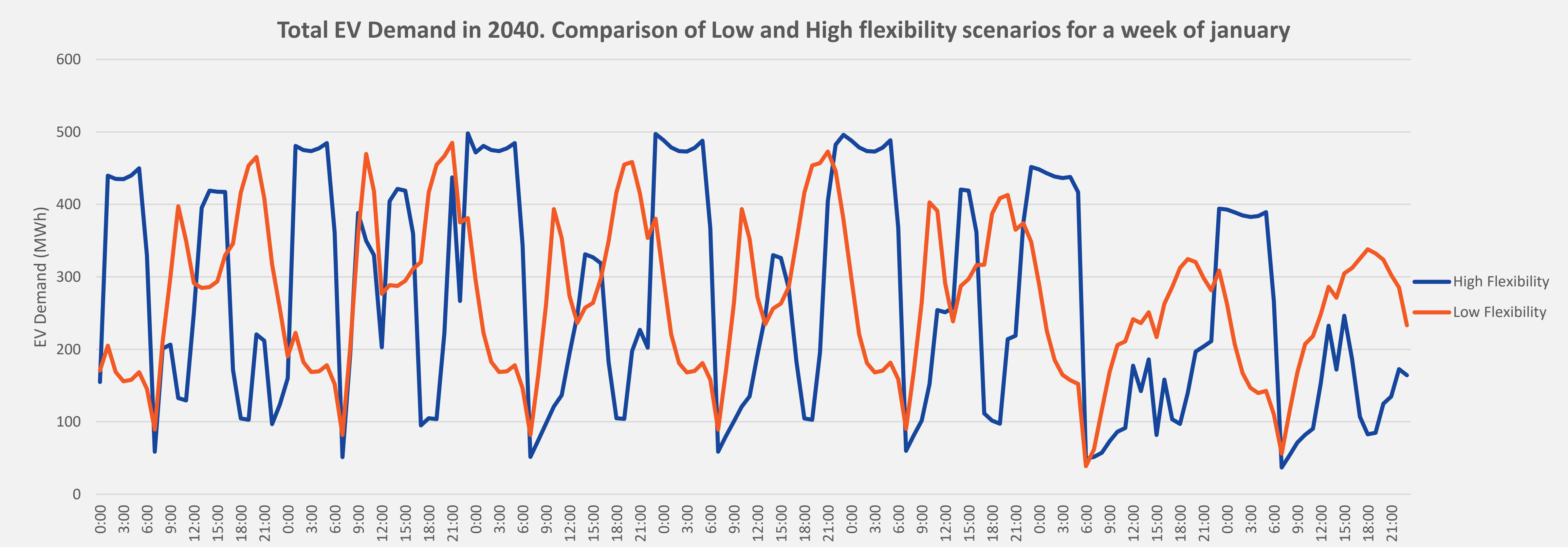
- Two smart charging scenarios are defined, with different levels of flexibility.
  - The choice of two contrasted scenarios allows to obtain clear and easy to understand results.

Rate of smart charging	S1 – Low flexibility	S2 – High flexibility
Uncontrolled charging	70%	10%
Smart-charging	30%	90%

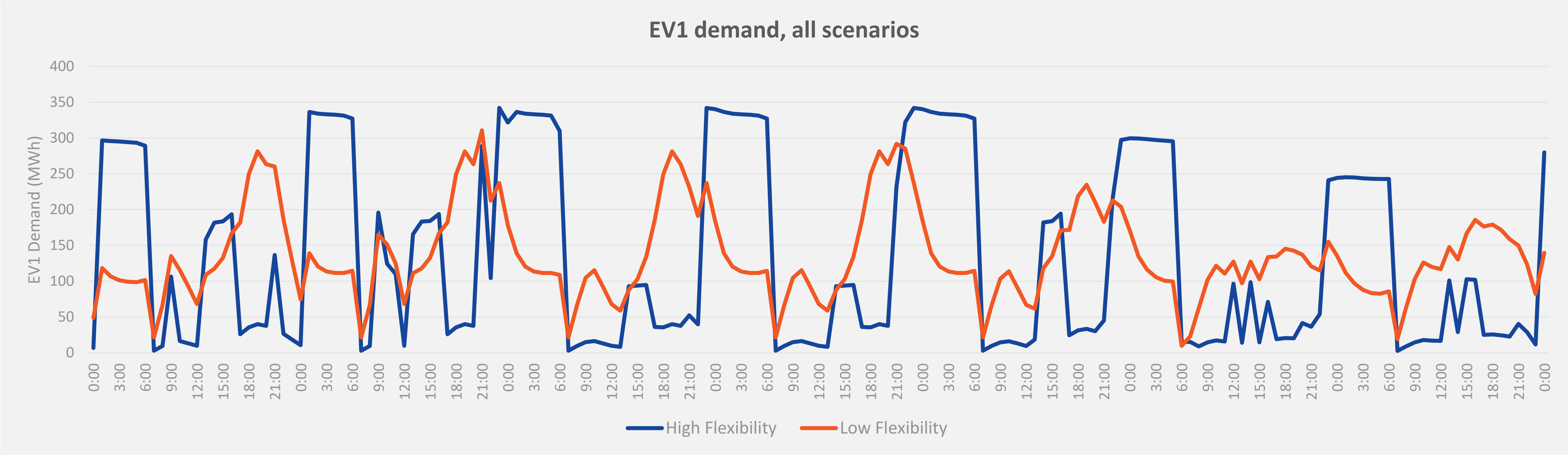
Percentages correspond to the volume of energy associated with each charging mode.

Aggregated Load Curve – all fleets

- These load curves result from the computation detailed on the previous slide. It corresponds to the aggregation of the load curves for the eight fleets.
  - The smart strategy prioritizes overnight charging, and to a lesser extent charging in the middle of the day.



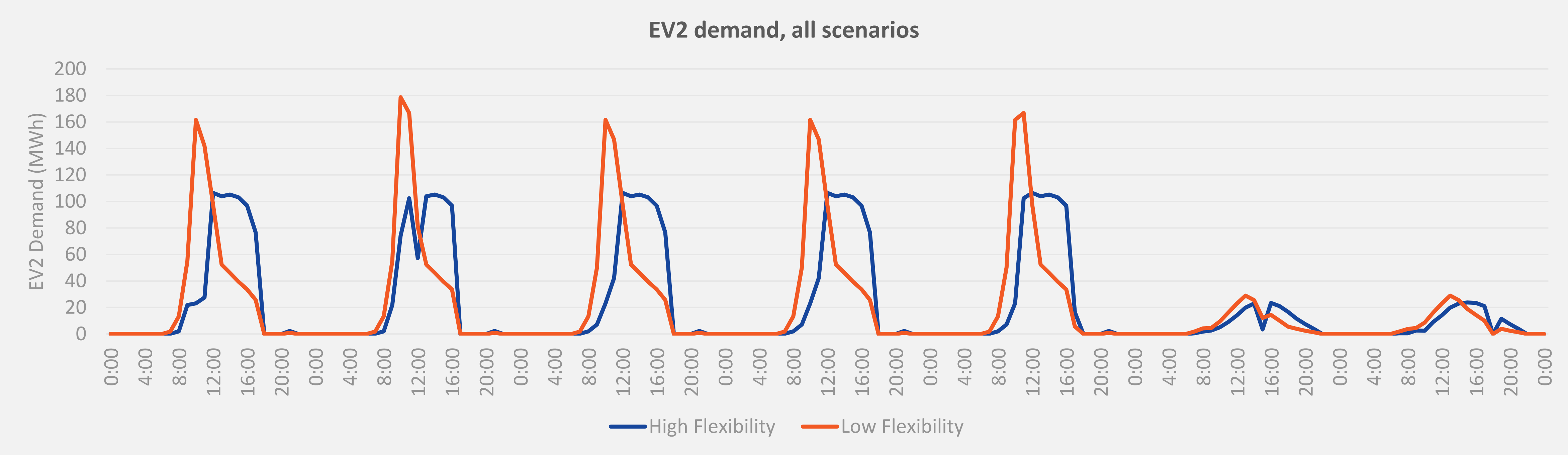
LDVs – Home (EV1)



- EV1 is the most important fleet in terms of demand (1 184 GWh / 2 375 GWh). It accounts for 50% of the final aggregated load curve.
- Fleet hypotheses
  - 15% day-charging
  - 85% night-charging
  - Reduced demand on weekends and wide night charging opportunity

Sources : ICCT hypotheses ; Electric Nation, UK, 2018

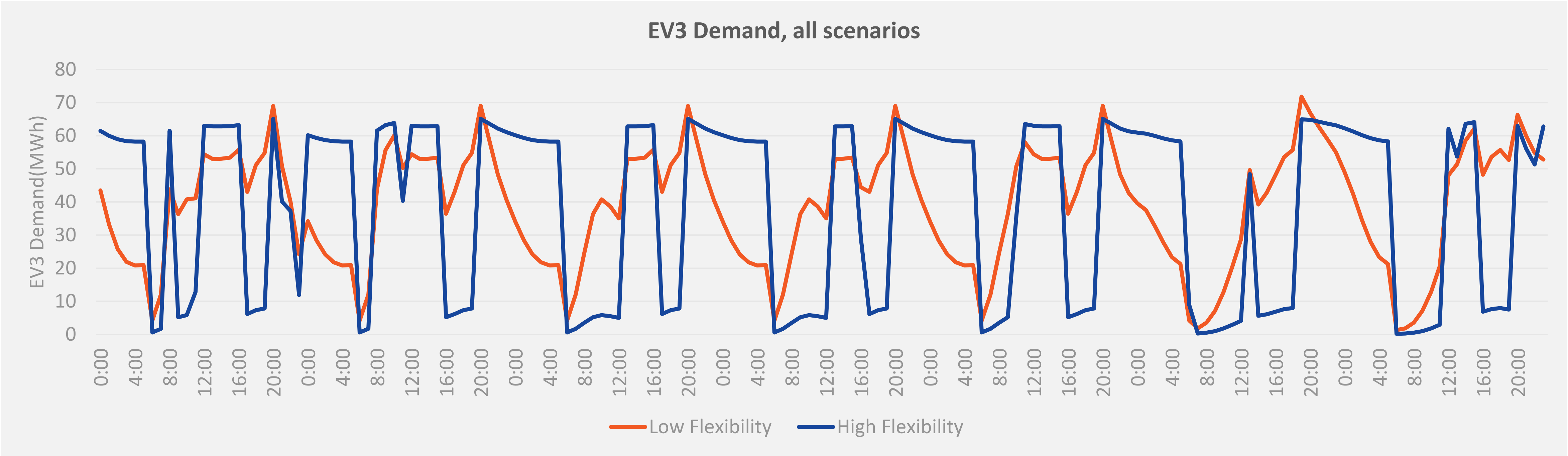
LDVs – Work (EV2)



- This fleet corresponds mainly to overday charging, with a peak of arrivals at 9am and a peak of departures at 5pm.

Sources : ICCT hypotheses ; https://ev.caltech.edu/dataset

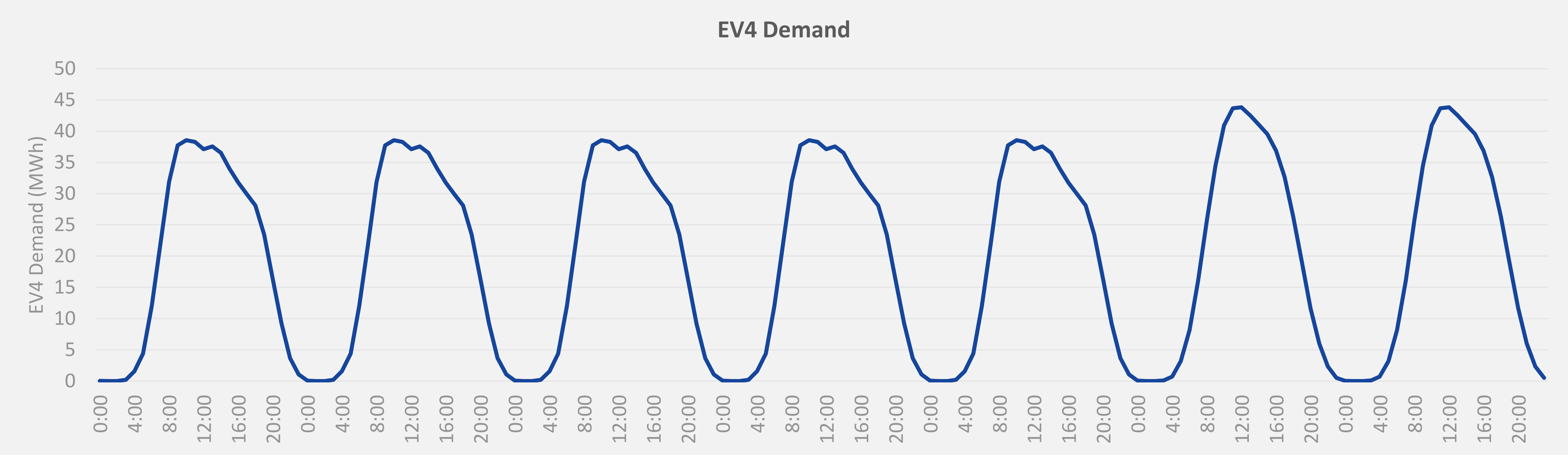
LDVs Public normal (EV3)



- The fleet is equally distributed between day charging and overnight charging vehicles.

Sources : ICCT hypotheses ; Belib Paris

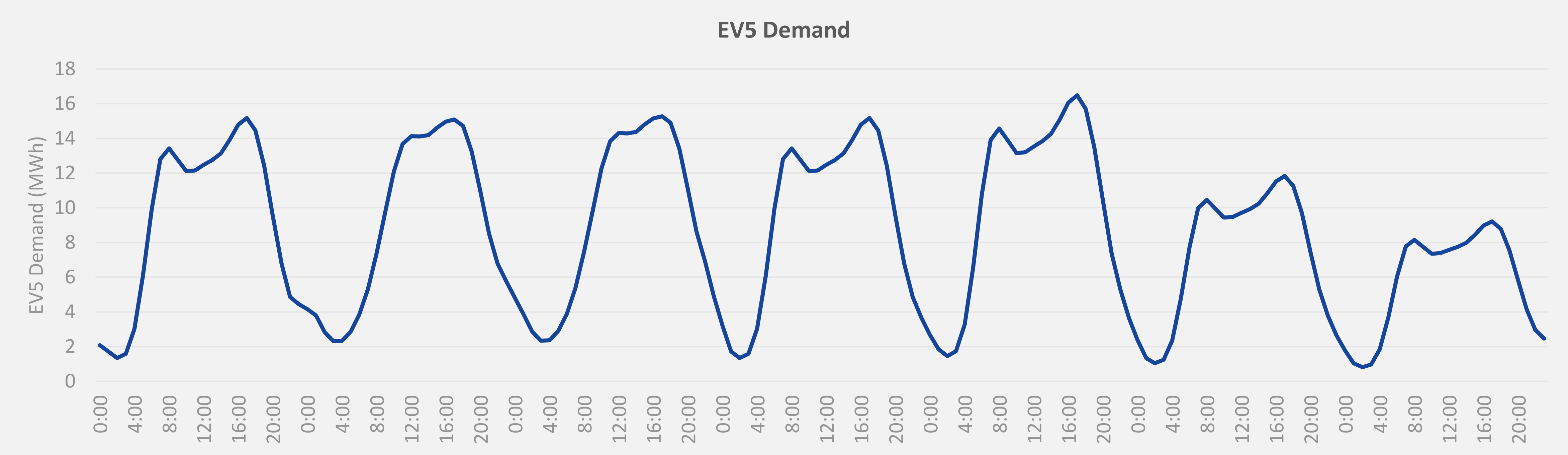
LDVs - Public fast (EV4)



- Public fast charging occurs mostly during day. Charging is higher during week-end than weekdays.

Sources : ICCT hypotheses ; https://ev.caltech.edu/dataset

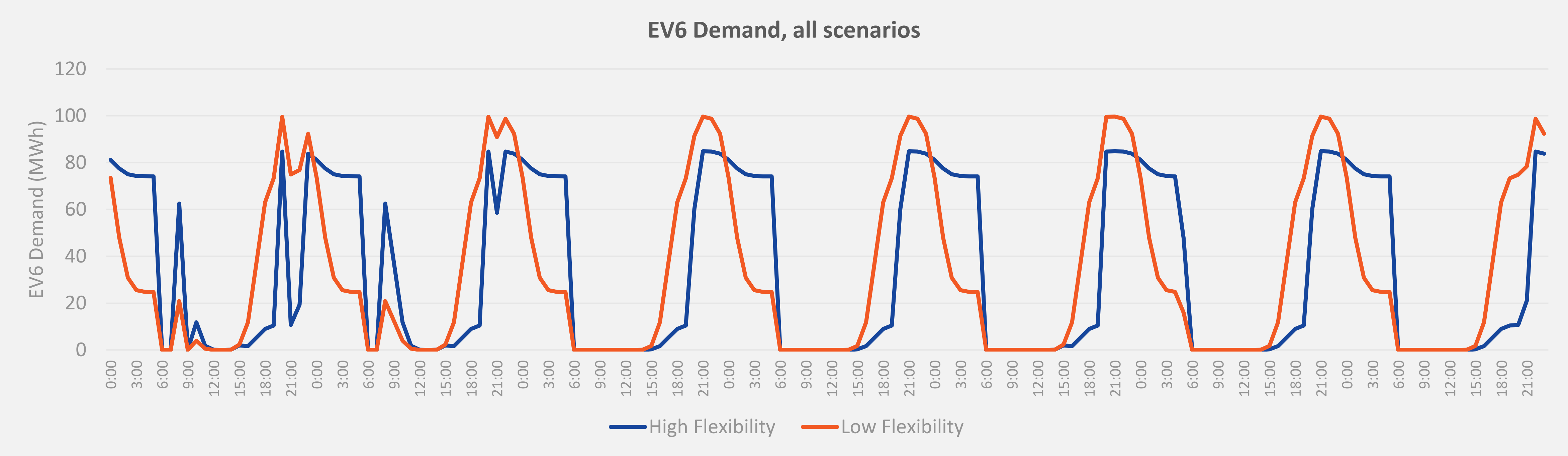
LDVs – Highways (EV5)



- Load curve based on actual highway data. Differences between working and rest days and peaks during summer vacations are taken into account.

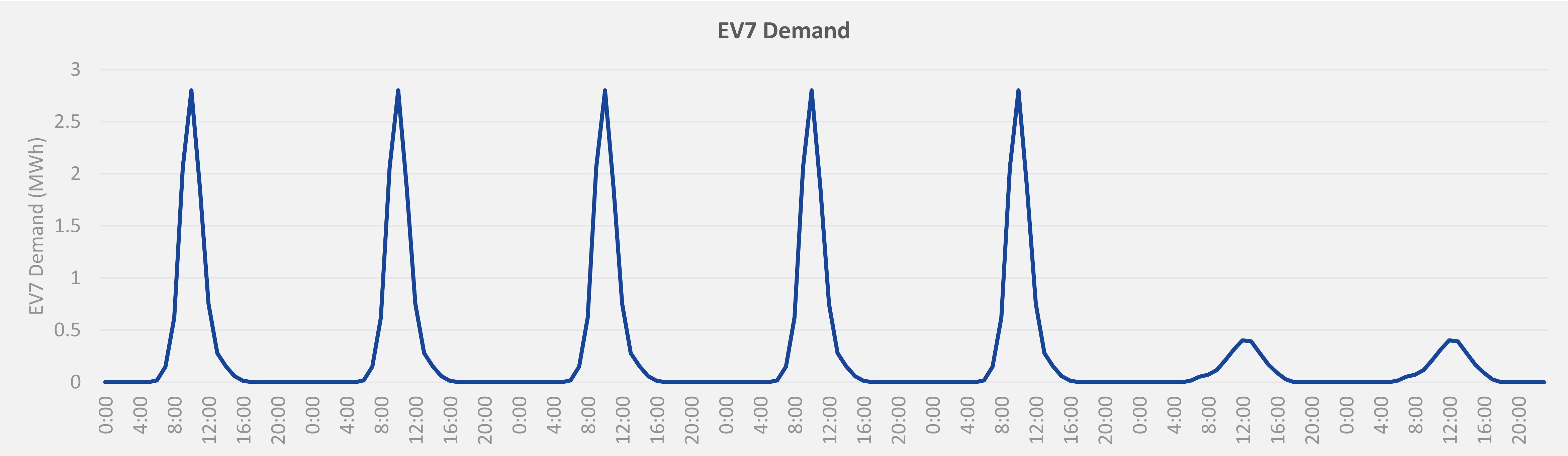
Sources : ICCT hypotheses ; Comptages SIREDO Tous véhicules sur les autoroutes en IdF. DRIEAT-if, 2022. [link]

HDVs – Depot charging (EV6)



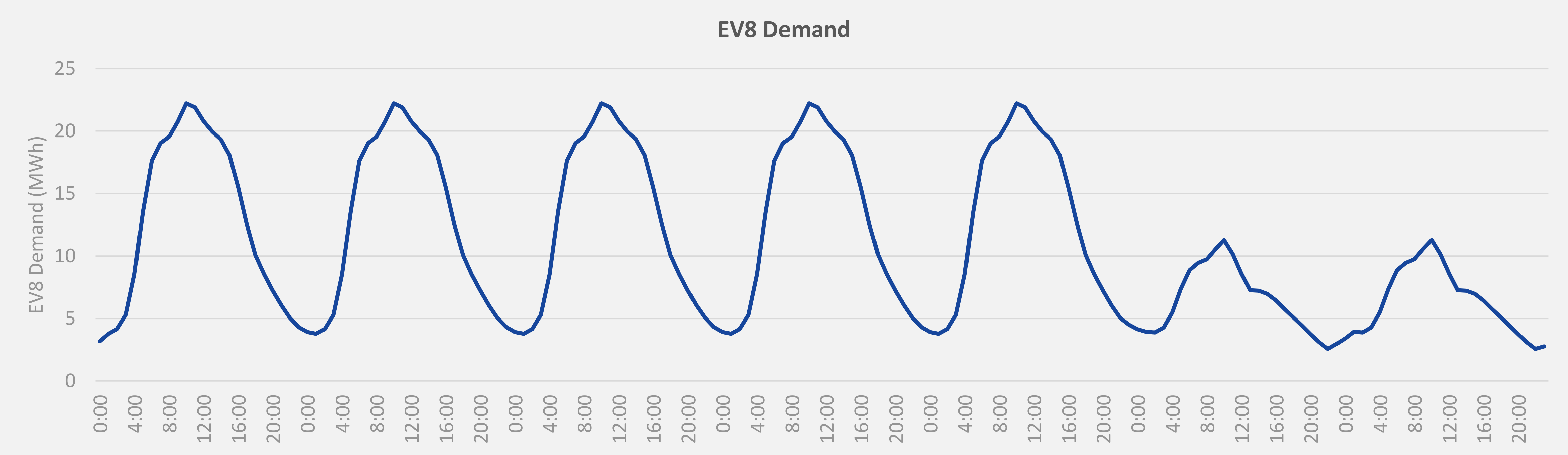
- EV6 represents HDVs and LCVs fleets charging at depots. The flexibility window is during night.

HDVs – Warehouses (EV7)



- Based on what is described in the report *Electrifying Eu City Logistics* (RAP and ICCT), the load is distributed during the day. Given the low share of this fleet in the total EVs consumption (0.2%), it does not impact significantly the overall load.
- The shape of the load curve is the same as for EV2 (work).

HDVs – Highway charging (EV8)



- The modelling is based on average traffic on highways.
- Hourly profile based on counting data for the Paris area[1]. In addition, weekly variations are assumed with a big drop during the weekends.

[1] Comptages SIREDO Poids Lourds, sur les autoroutes en IdF. DRIEAT-if, 2022. [link]

Geographical distribution of the EV load in the study area

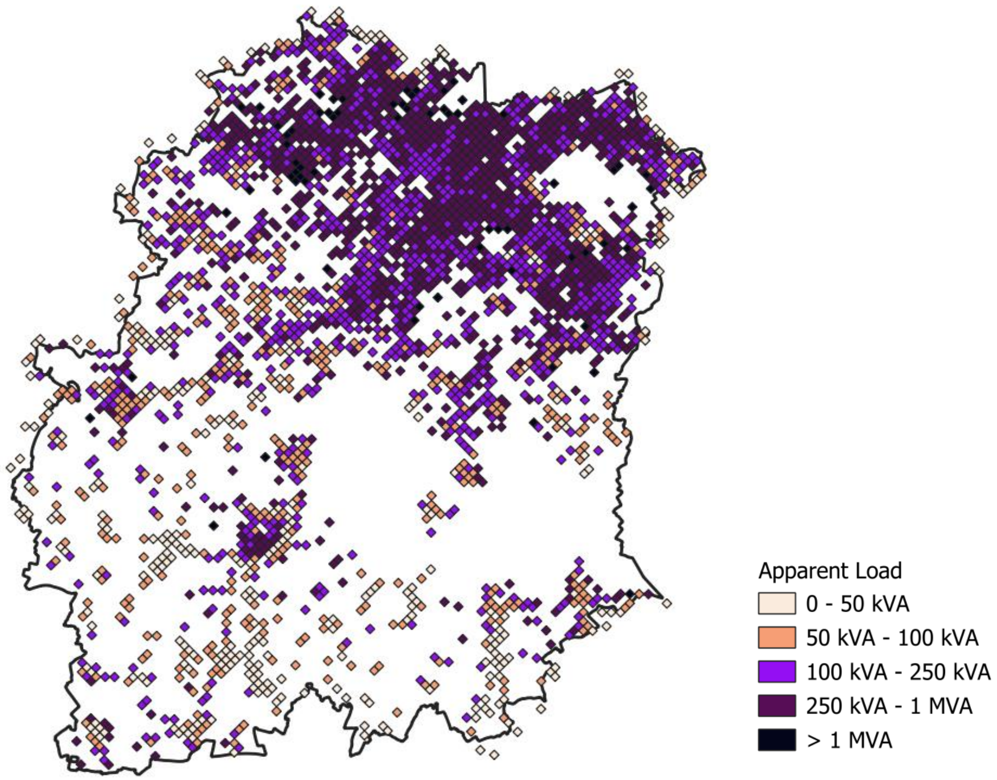
Fleet Name	Type of EV	Charging type	Allocation key	Source
EV1	eLDV	Home	Number of house and apartment building with parking	INSEE
EV2		Work	Number of employees	SIRENE
EV3		Public normal	Number of public parking and number of apartment building without parking	INSEE / BD TOPO
EV4		Public fast	Number of public parking and gas station	BD TOPO data.gouv (gas stations)
EV5		Highway fast / ultrafast	Highway stations	BD TOPO
EV6	eHDV	Depot	Zones housing “transport and warehousing” activities	French activity nomenclature (INSEE)
EV7		Warehouses	Zones housing “transport and warehousing” activities	French activity nomenclature (INSEE)
EV8		Public fast/ultrafast (incl. Highways)	Gas stations and Highway stations	BD TOPO data.gouv (gas stations)

Methodology and assumptions

5. Power flow simulations

Principles of the Physical Simulation

- Simulations of power flows on the MV distribution network are performed at a critical moment, in view of the considered assumptions.
- This critical moment is the **consumption peak**, representing the highest annual consumption within the area.
- 2 KPIs are computed and analyzed : the **apparent load** and the **voltage drop**, at MV/LV stations.
- KPIs are observed using 1km² squares mesh. They can also be observed at the asset (MV/LV substation and MV line) level.
- Voltage drops are considered acceptable as long as they do not exceed 5%.
- At an asset level, apparent load is **acceptable as long as it is lower than the nominal capacity of the asset**. Otherwise, the asset is considered to be **overloaded**.



Exemple of apparent load observed through 1km² meshes : Apparent load in the low flexibility scenario, at peak consumption

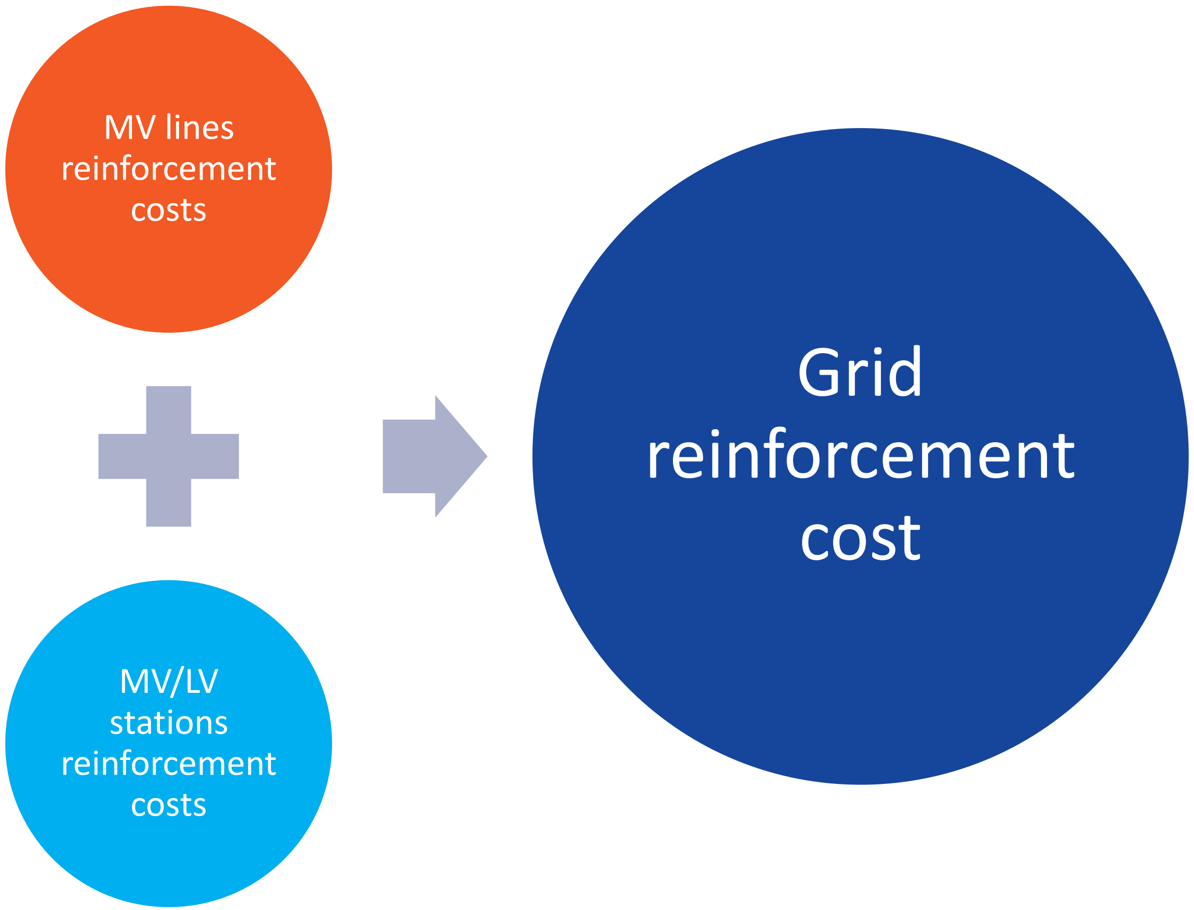
Note : Part of the rural territory is operated by a local network operator, representing 2.3% of the total population. This is taken into account so that it doesn't affect the results

Methodology and assumptions

6. Calculation of reinforcement needs and related costs

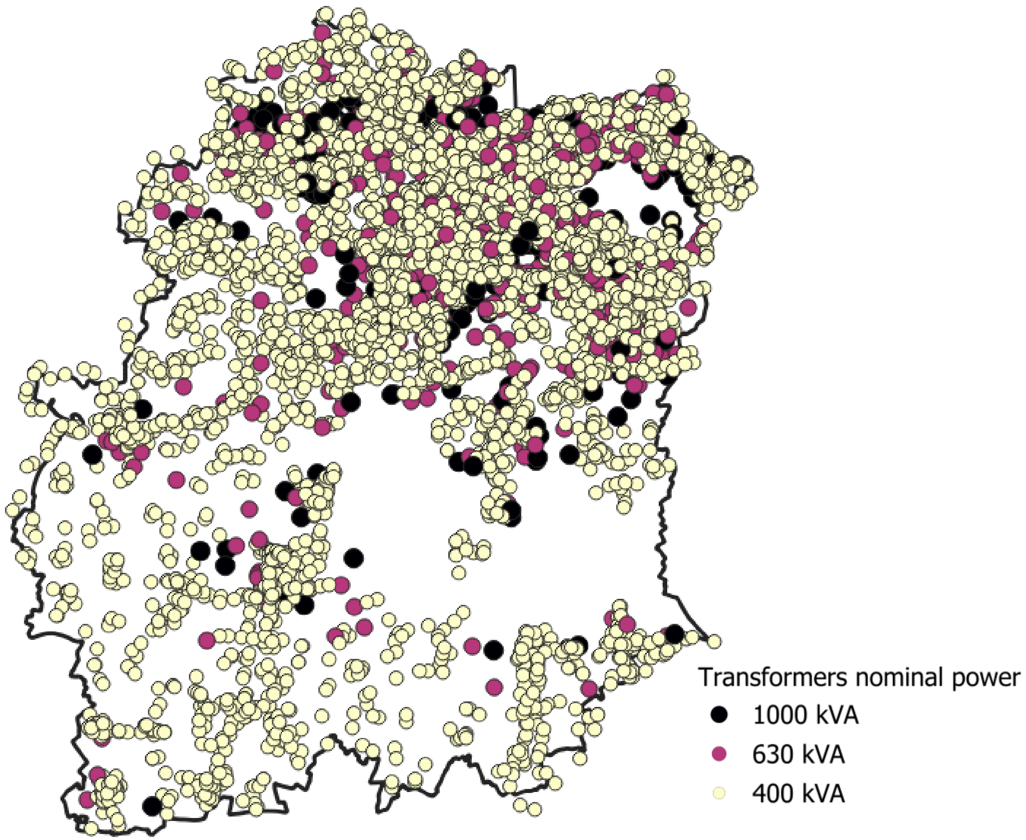
Grid reinforcement needs - methodology

- The estimated reinforcement costs relate to the MV network.
- **A similar approach for lines and stations**
  1. A nominal capacity is assigned per line and per transformer, based on the 2022 demand and a catalogue of nominal capacities used by the DSO.
  2. For each of the lines or stations, the reinforcement is considered necessary if the maximum power transited in 2040 exceeds the nominal capacity.
  3. The cost of reinforcement is estimated for both MV lines and MV/LV substations.



MV/LV Stations

MV/LV substations reinforcement



Nominal powers assigned to transformers for the 2022 situation.

Methodology

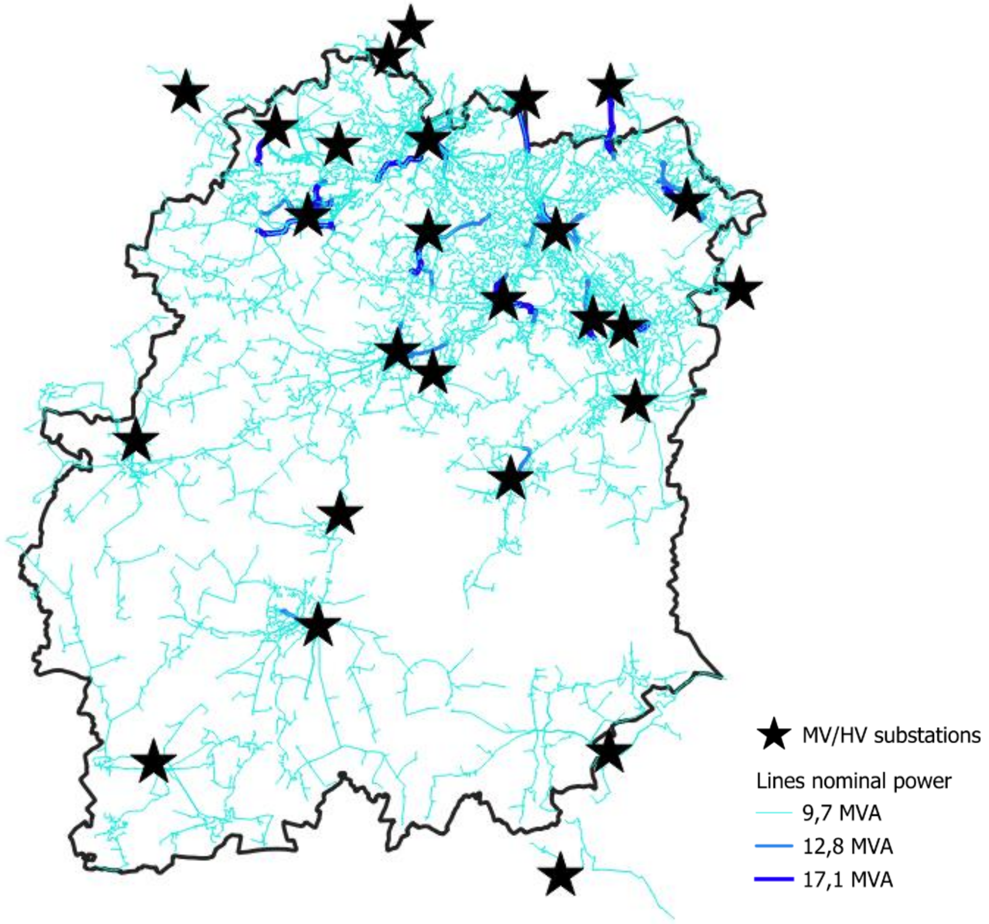
- Reinforcement is considered only if the maximum load in 2040 exceeds the nominal capacity of the station.
- The cost in euros is expressed as a linear function, reflecting a fixed cost and a variable cost depending on the reinforcement power required.

$$C_{station} = 20\,000 + 30 \ * Overload$$

$C_{station}$ being the reinforcement cost associated to a MV station, in €, $Overload$ the difference of peak load at the station in 2040 and its nominal capacity.

Sources :
- LES RACCORDEMENTS AU RÉSEAU ÉLECTRIQUE
- Another Source of Inequity? How Grid Reinforcement Costs Differ by the Income of EV User Groups

Lines reinforcements



Nominal capacities assigned to lines for the 2022 situation.

Methodology

- MV lines are designed to meet the N-1 safety criterion, incorporating a 50% security capacity margin. **A line is considered overloaded if the power transmitted exceeds 50% of its capacity**.
- The cost of reinforcements on a line depends little on capacity. The cost model is a function proportional to the length of the section to be reinforced.

$$C_{lines} = 120 \ * length$$

C_{lines} being the reinforcement cost associated to a MV line, in €, $length$ the length of the section to be reinforced, in meter.

Sources :
- LES RACCORDEMENTS AU RÉSEAU ÉLECTRIQUE
- Should we reinforce the grid? Cost and emission optimization of electric vehicle charging under different transformer limits

Methodology and assumptions

7. Sensitivity analysis : addition of V2G

Hypotheses : Fleets and V2G Scenario

- A third scenario is built in this sensitivity analysis. It sets a rate of 10% for Vehicle-to-Grid (V2G) in 2040. Fleets that are able to perform V2G are the same as the fleets able to perform smart charging (as defined above).
- A specific tariff for the V2G fleets has been designed : this tariff aims at reflecting the actual state of the network, taking into account EV loads. It is built upon the observed consumption peaks in the *High Flexibility* scenario. Thus, the impact of V2G is evaluated with regards to this *High Flexibility* scenario.

Rate of charging types	S3 – V2G
Uncontrolled charging	10%
Smart-charging (ToU)	80%
V2G	10%

Percentages correspond to the volume of energy associated with each charging mode.

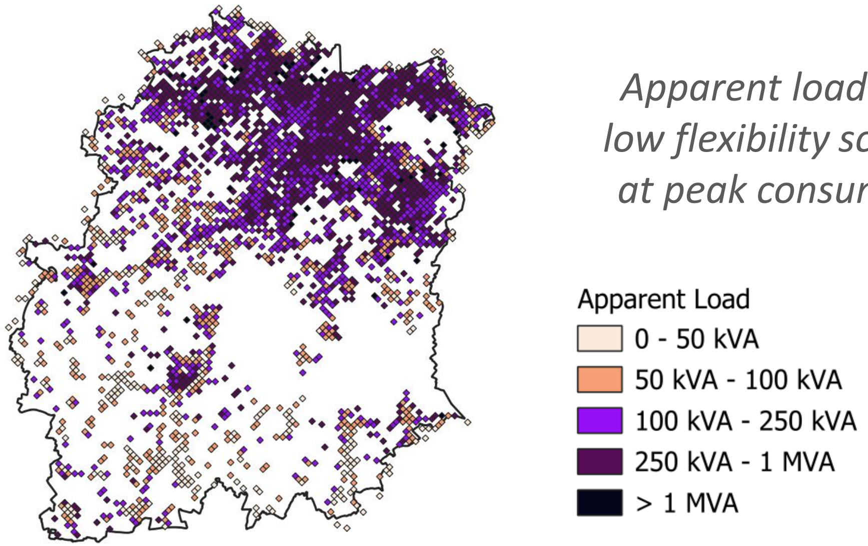
Results

Impact of high flexibility

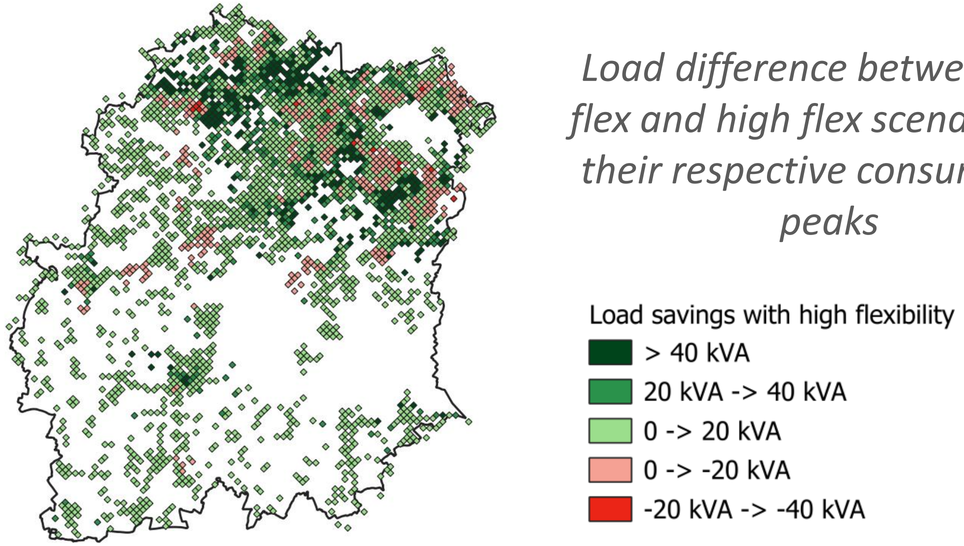
Results of the Network Simulation

- The area's MV network has been simulated for both *high flexibility* and *low flexibility* scenarios, each at their respective consumption peaks
  - ***High Flexibility* peak : 1 423 MW**
  - ***Low Flexibility* peak : 1 511 MW**
  - Mean apparent load per MV/LV substation on the upper map is 230 kVA.
  - In comparison, the consumption peak in 2022 is 1134 MW.

- Higher flexibility helps reduce the maximum load at the majority of MV/LV substations. Higher load values are displayed in the northern part of the area, which is urban, compared to the more rural south.



Apparent load in the low flexibility scenario, at peak consumption



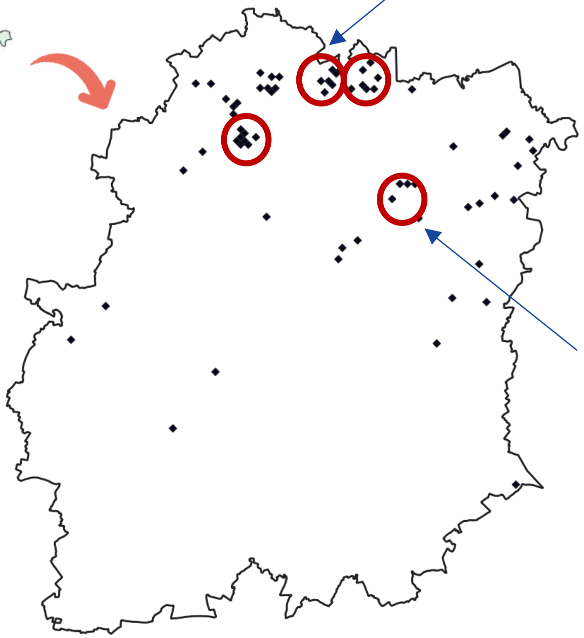
Load difference between low flex and high flex scenarios, at their respective consumption peaks

Results : Focus on high load areas

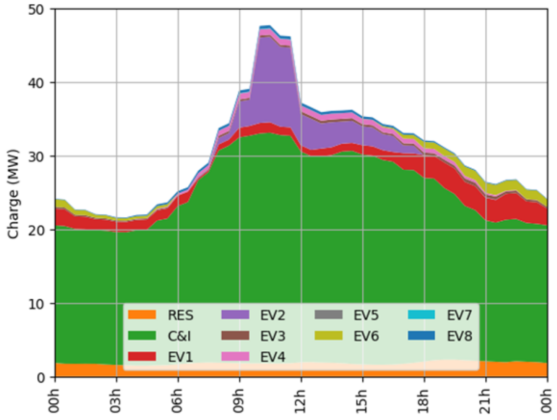
Diving into high load areas : Here is considered the local network at the consumption peak in the *low flex* scenario. The peak occurs in January at 10am. The traditional 6pm consumption peak has been displaced by EVs.
The high flex scenario peak also occurs in January, at 2pm.

- Several areas gather clusters of transformers presenting more than 1 MVA of apparent load.
- These clusters are mostly representing working hubs, with lots of employees (EV2).
- Highway stations are critical points as well (EV5, EV8).
- Most of these critical points are shared by both scenarios. They highlight the concentrated demand for workplace and public charging, in contrast to the more dispersed demand for home charging.

In black, IRIS hosting more than 5000 employees

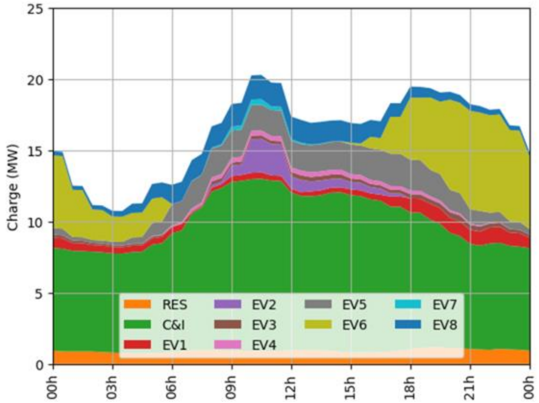


Apparent load at consumption peak, where load is > 1 MVA. ***Low Flex scenario***[1]



Load curve in a business zone, around consumption peak

In the three northernmost areas, EV2 predominantly causes the consumption peak. These busy tertiary areas have a significant number of workplace charging stations.



Load curve in an area containing a highway station, around consumption peak

This eastern area is host to a highway station. Hence, both EV5 and EV8 participate in creating an important load.

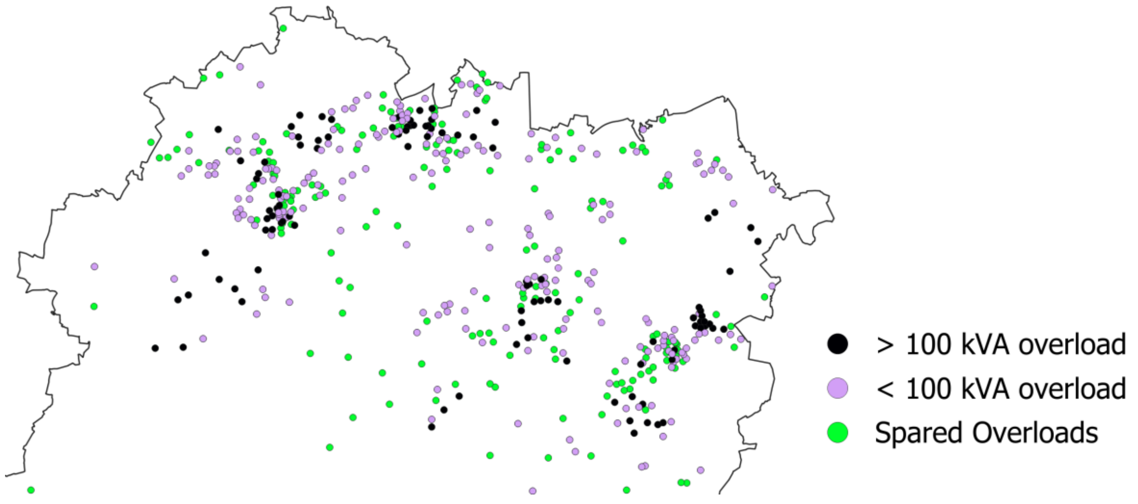
[1] Load curves for the *High Flex* scenario can be found in Appendix 1

Reinforcement needs

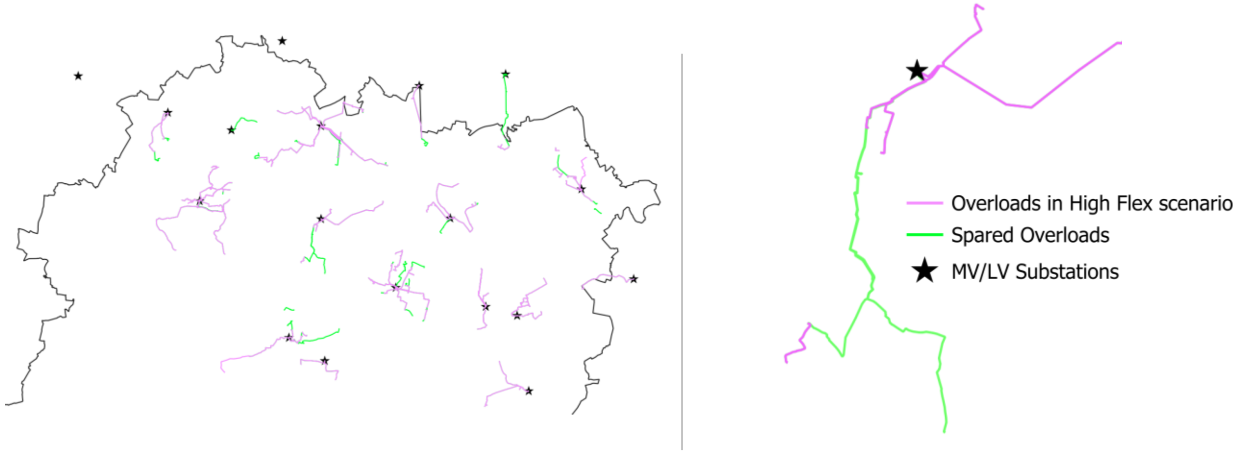
MV/LV substations and MV lines are now considered to be sized as proposed in the hypotheses section. Then, it is possible to map those where overloads occur, i.e. assets where the apparent load is higher than their *calculated nominal power*.

- Zones subject to transformer reinforcements are the same zones undergoing high apparent load (i.e., mostly in the urban part of the area).
- More transformers are subject to reinforcement in the *low flexibility* scenario.
- Lines subject to reinforcement are most of the time HV/MV substation outputs.
- Once again, more lines need reinforcement in the *low flexibility* scenario.

Note : Maps presented on this slide are zooms of the northern part of the area, for illustrative purposes. Maps for the whole area can be found in the appendices.

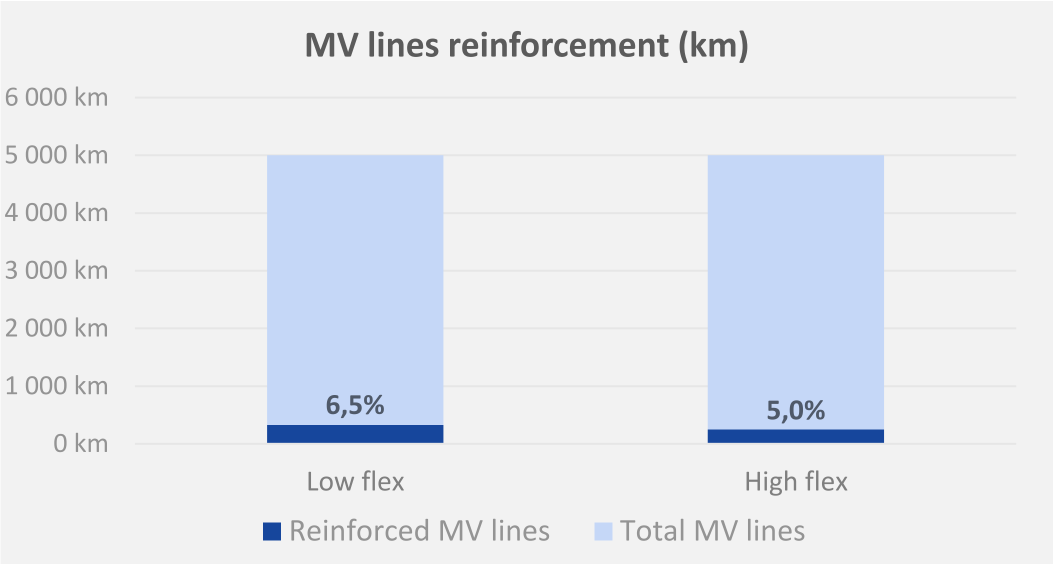


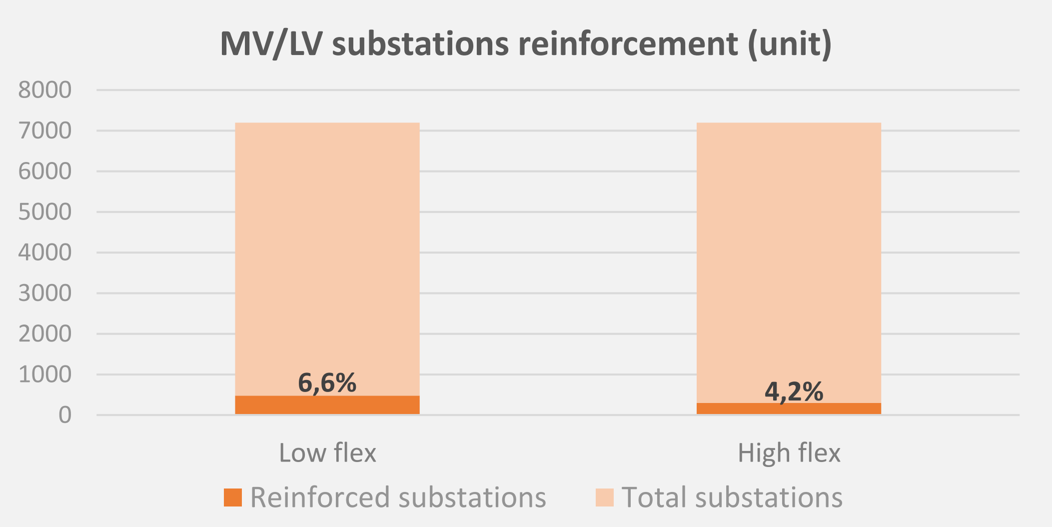
Transformers overloads *: Green assets are transformers subject to an overload in the low flex scenario, but not in the high flex scenario. These are the concrete gains of high flex.*



Line overloads *: Whole area (left) and zoom at a HV/MV substation (right). Spared reinforcements in the high flex scenario are displayed in green as well.*

Reinforcement needs





- In both scenarios, less than 10% of all the assets are subject to reinforcement.
  - The network under study possesses ample capacity margins, with most assets capable of accommodating significant electric vehicle (EV) loads.
- In the *High Flexibility* scenario, the need for kilometers of line reinforcements is **23% lower** as well, than in the *Low Flexibility* scenario.
- The *High Flexibility* scenario allows a **37% reduction** of the amount of transformers subject to reinforcement, compared to the *Low Flexibility* scenario.

Economic results

- Yearly reinforcement costs in the area are estimated between 2 M€ and 3 M€ in both scenarios.
  - *Low Flexibility* is indeed a more expensive scenario, as expected **(+33%)**.
- ENEDIS predicts[1] 2.7 M€ per year dedicated to network reinforcements in this area, at a 2030s horizon.
  - ENEDIS' network reinforcement figures include LV grids, MV grids and substations.
- Costs per EV have been deduced from overall costs.
  - By dividing the costs between LCVs and HDVs on the basis of their annual energy demand, the costs are estimated at :
    - **Between €40 and €70 per LDV**
    - **Between €750 and €1 100 per HDV**

Scenario	Cost (M€ /y)
Low Flexibility	2,8
High Flexibility	2,1

Reinforcement costs in each scenario, per year between 2022 and 2040

The calculation of reinforcement costs is based on a number of assumptions that have been made to fill in the gaps in the available information. Given the considerable uncertainties involved, these values should be interpreted with caution.

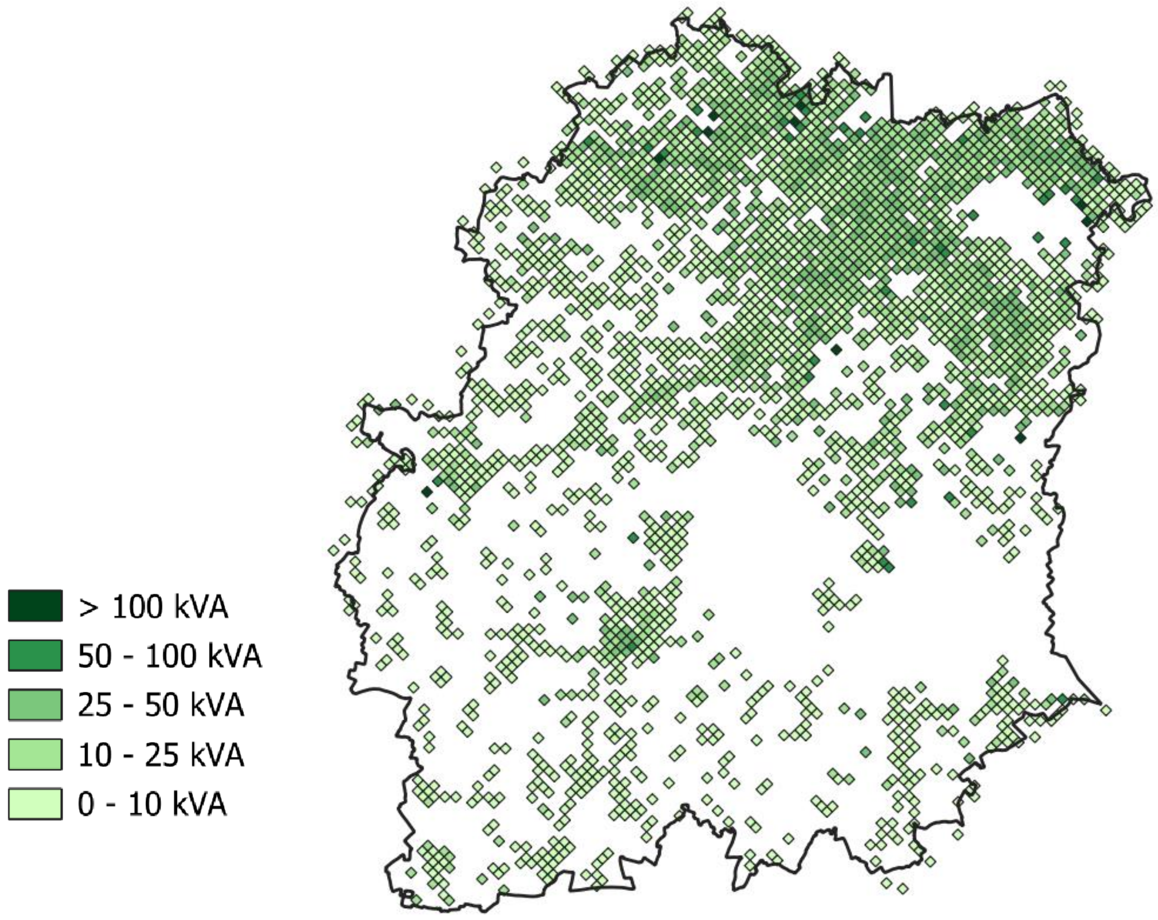
[1] Data from ENEDIS' *Network Development Plan*, according to local requirements, considering its number of MV/LV transformers.

Results

Impact of V2G

Results of the Network Simulation

- Simulating the area's MV network in the V2G scenario, the consumption peak occurs at the same moment than in the high flexibility scenario. However, V2G allows this peak to be 3,4% smaller:
  - ***High Flexibility* peak : 1 423 MW**
  - ***V2G* peak : 1 374 MW**
- V2G benefits from a tariff that matches the network state, taking into account both the baseload and the projected EV demand in 2040 in the *high flexibility* scenario, resulting in load savings across all sections of the area.

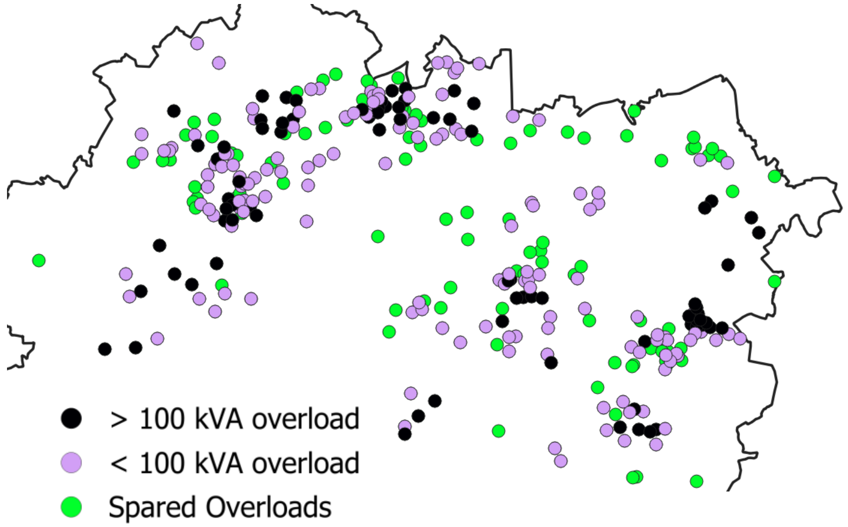


Load savings in the V2G scenario, compared to the high flex scenario

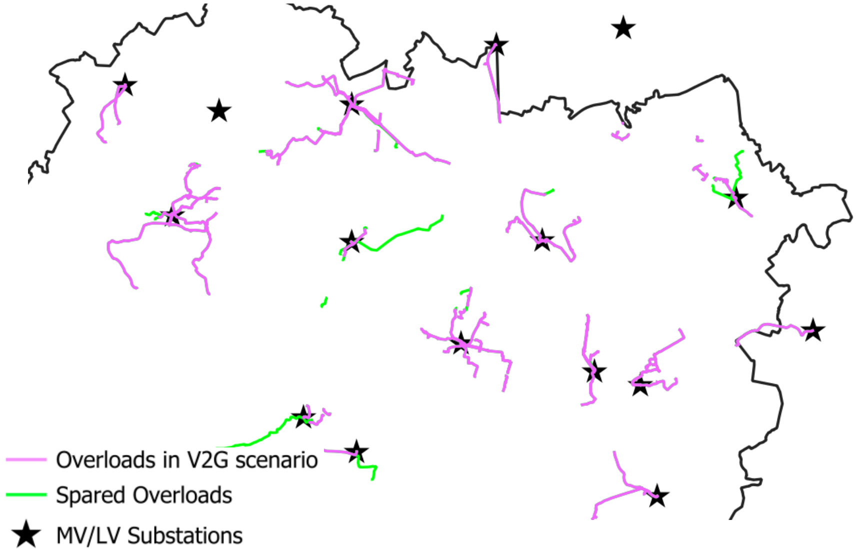
Reinforcement needs

MV/LV substations and MV lines share the same capacities in the V2G scenario than in the previously studied scenarios, allowing comparisons.

- As in the two previously studied scenarios, overloads are concentrated in the urban part of the area.
- As expected, V2G lowers the amount of observed overloads, especially compared to the *high flexibility* scenario.
- Clusters of loads are still visible, representing less flexible demand, such as highway charging (no flexibility at all) or workplace charging (tighter flexibility window).



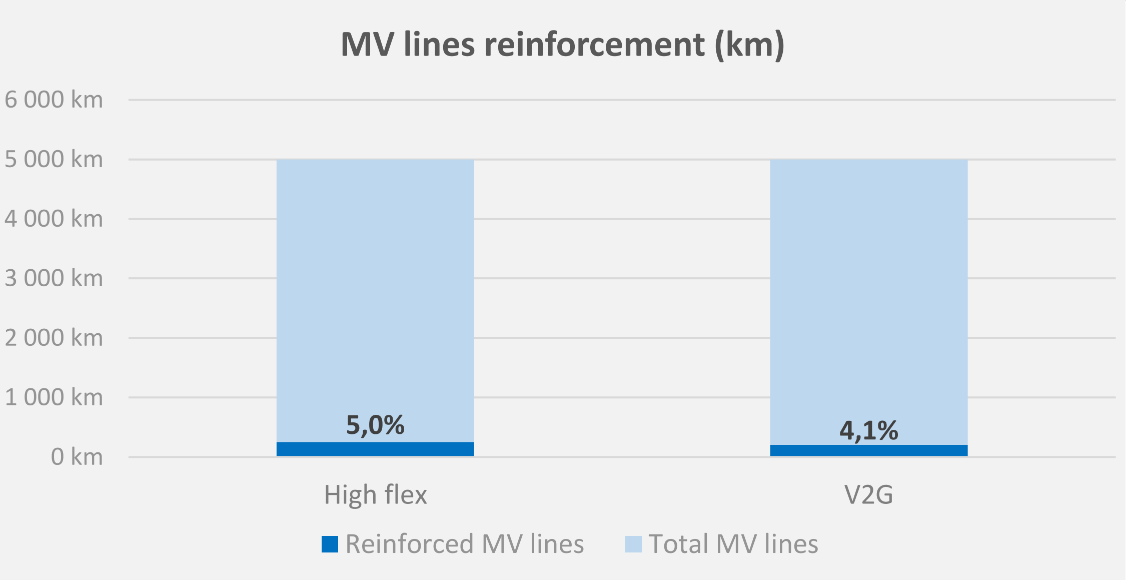
Transformers overloads *: Green assets are transformers subject to an overload in the high flex scenario, but not in the V2G scenario.*

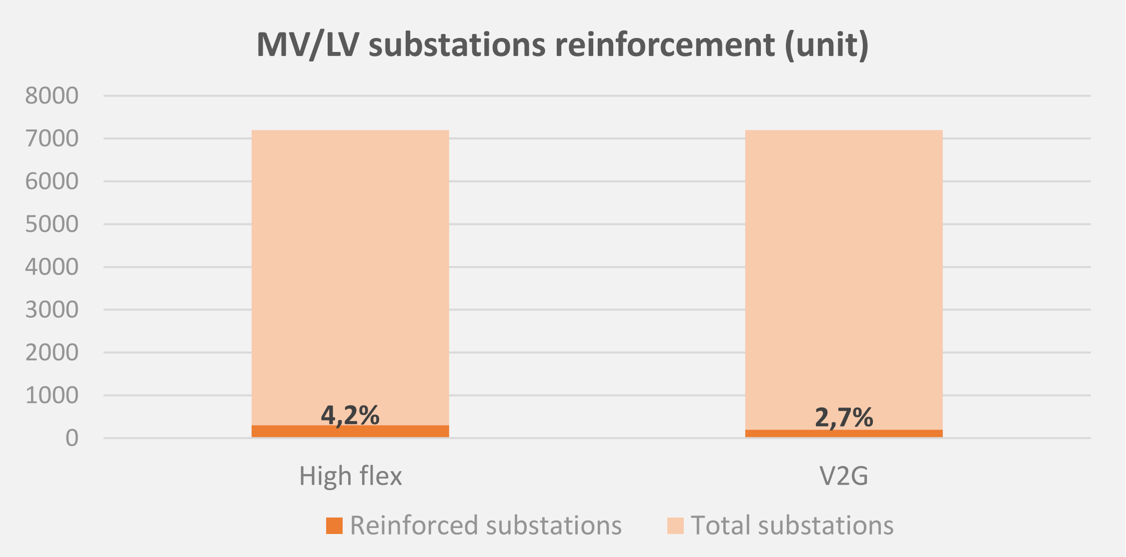


Line overloads *: Spared overloads overloads in the V2G scenario, compared to high flex, are represented in green*

Note : Maps presented on this slide are zooms of the northern part of the area, for illustrative purposes. Maps for the whole area can be found in the appendices.

Reinforcement needs and costs





- The V2G scenario allows a **18%** reduction in the need for line reinforcements, compared to the *High Flexibility* scenario.
- It allows a **34%** reduction in the need for substation reinforcements as well.

Scenario	Cost (M€ /y)
V2G	1,6
High Flexibility	2,1

- The V2G scenario also admits a lower estimated monetary cost, which is **24%** lower than *High Flexibility*'s.

General Conclusions of the Study

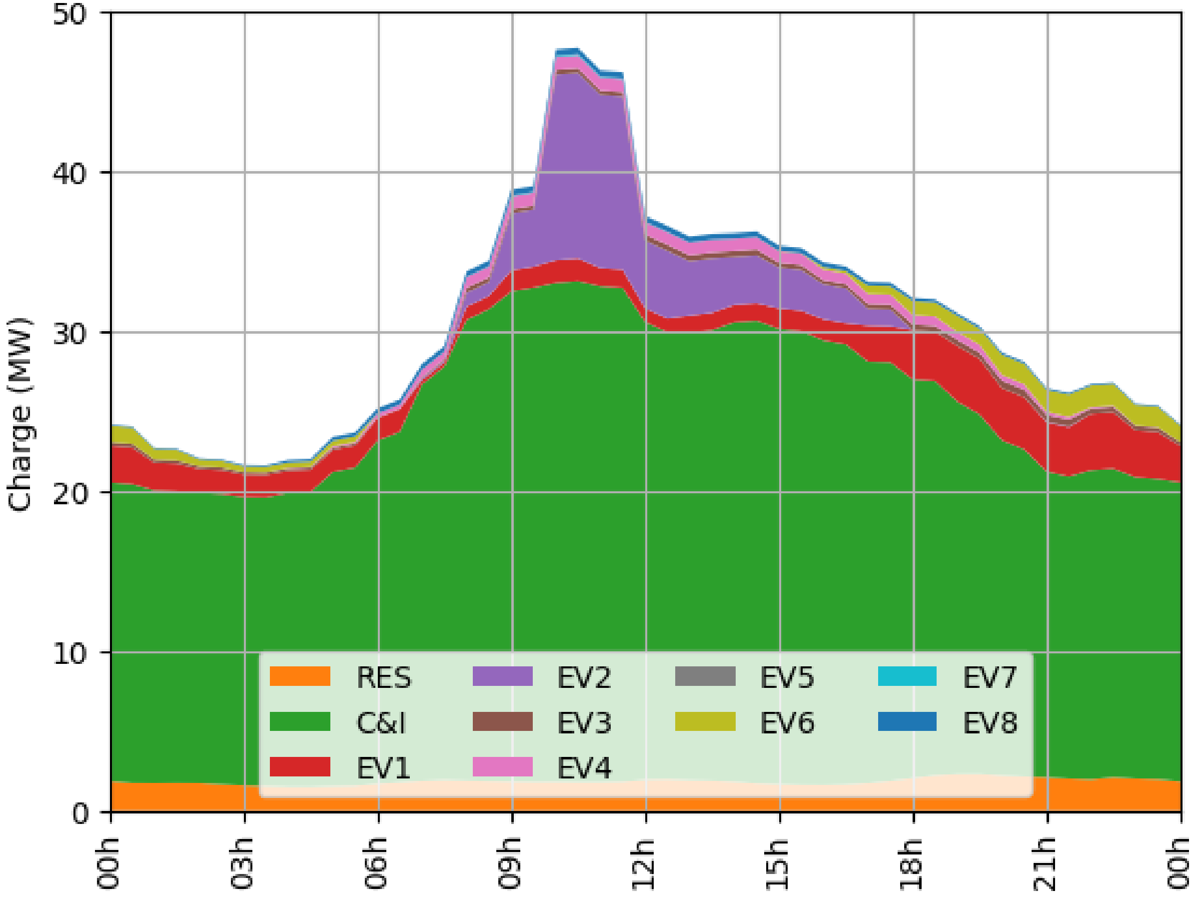
- A significant increase in the number of electric vehicles has the potential to create power peaks that will require reinforcement of the MV network.
- Even with a low penetration of smart charging, the need for reinforcement seems to be caped at 10% of the MV network.
- Nevertheless, an ambitious deployment of smart charging has the potential to reduce the cost of reinforcement by 25%.
- The addition of a marginal share of V2G driven by a tariff that reflects local constraints makes it possible to reduce reinforcement costs even further, by up to an additional 25%.

Appendices

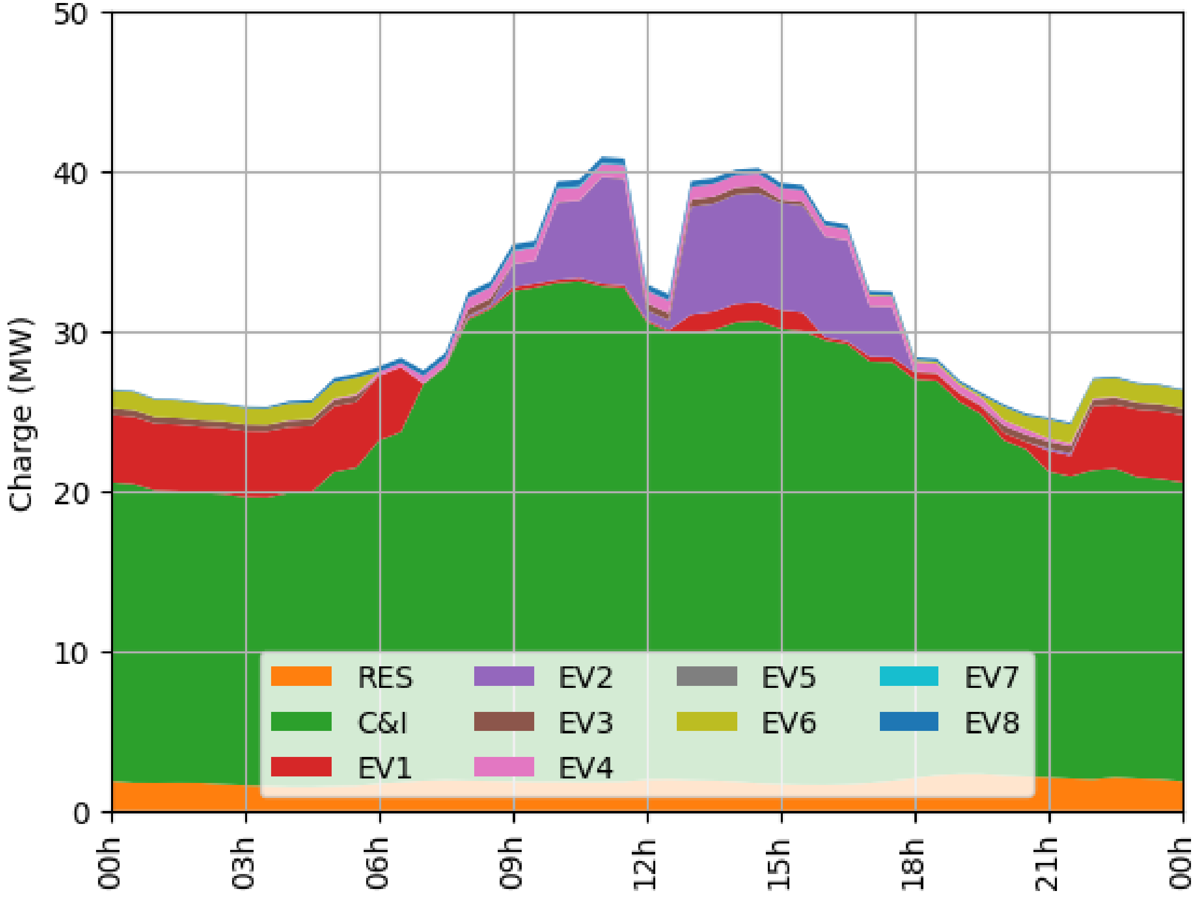
Appendix 1 : Business zone

Note : RES corresponds to residential consumption. C&I corresponds to commercial and industrial consumption

- Load curves in a business zone at the peak consumption in low flex and high flex scenarios.



Low Flexibility scenario

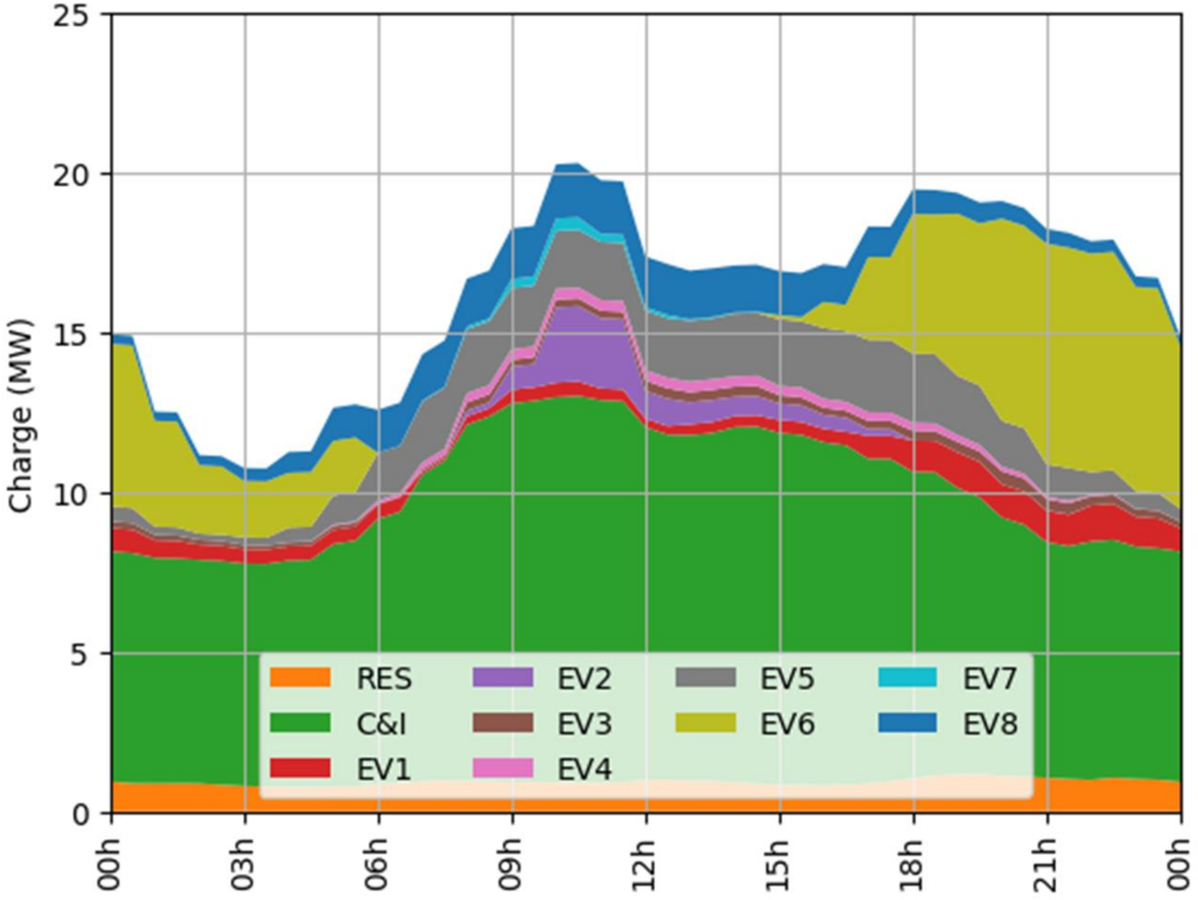


High Flexibility scenario

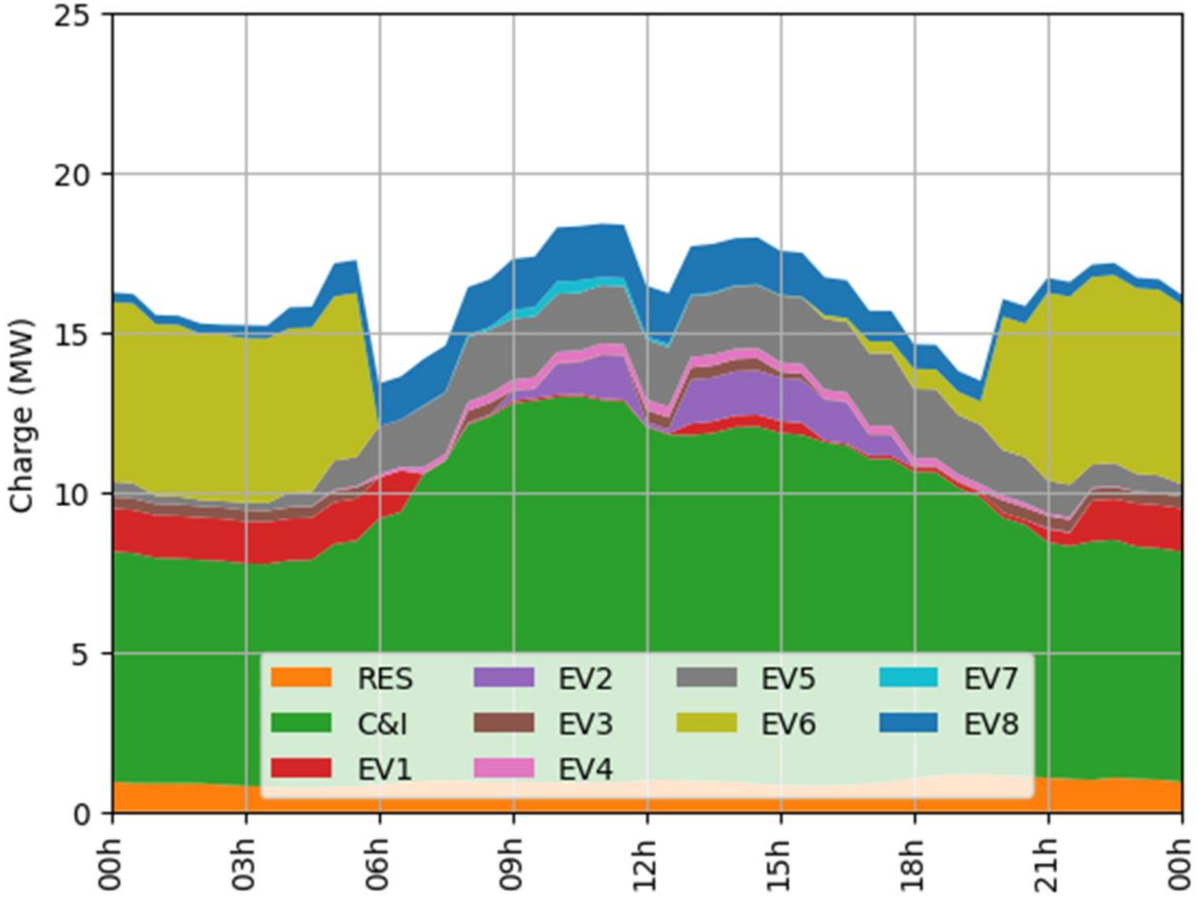
Appendix 1 : Higway station area

Note : RES corresponds to residential consumption. C&I corresponds to commercial and industrial consumption

- Load curves in a highway station area at the peak consumption in low flex and high flex scenarios.



Low Flexibility scenario

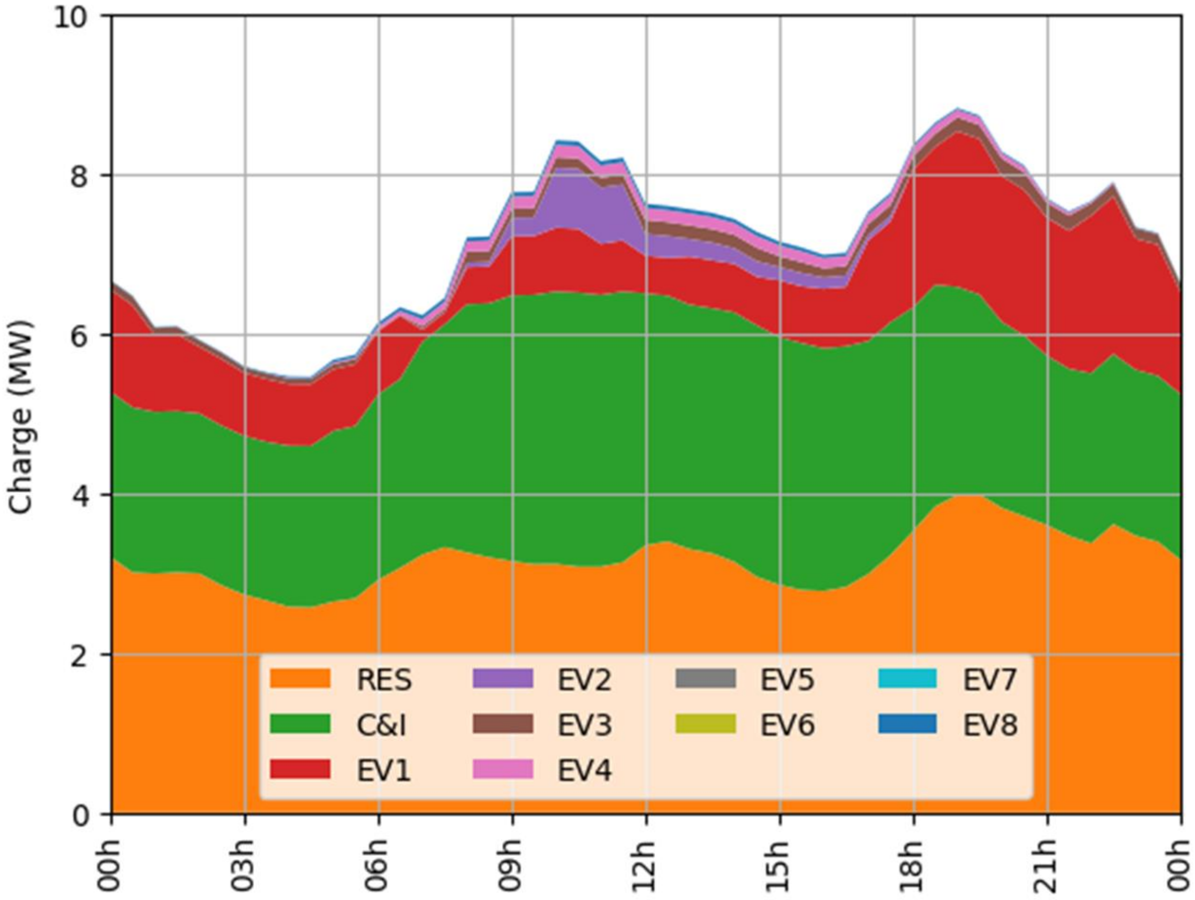


High Flexibility scenario

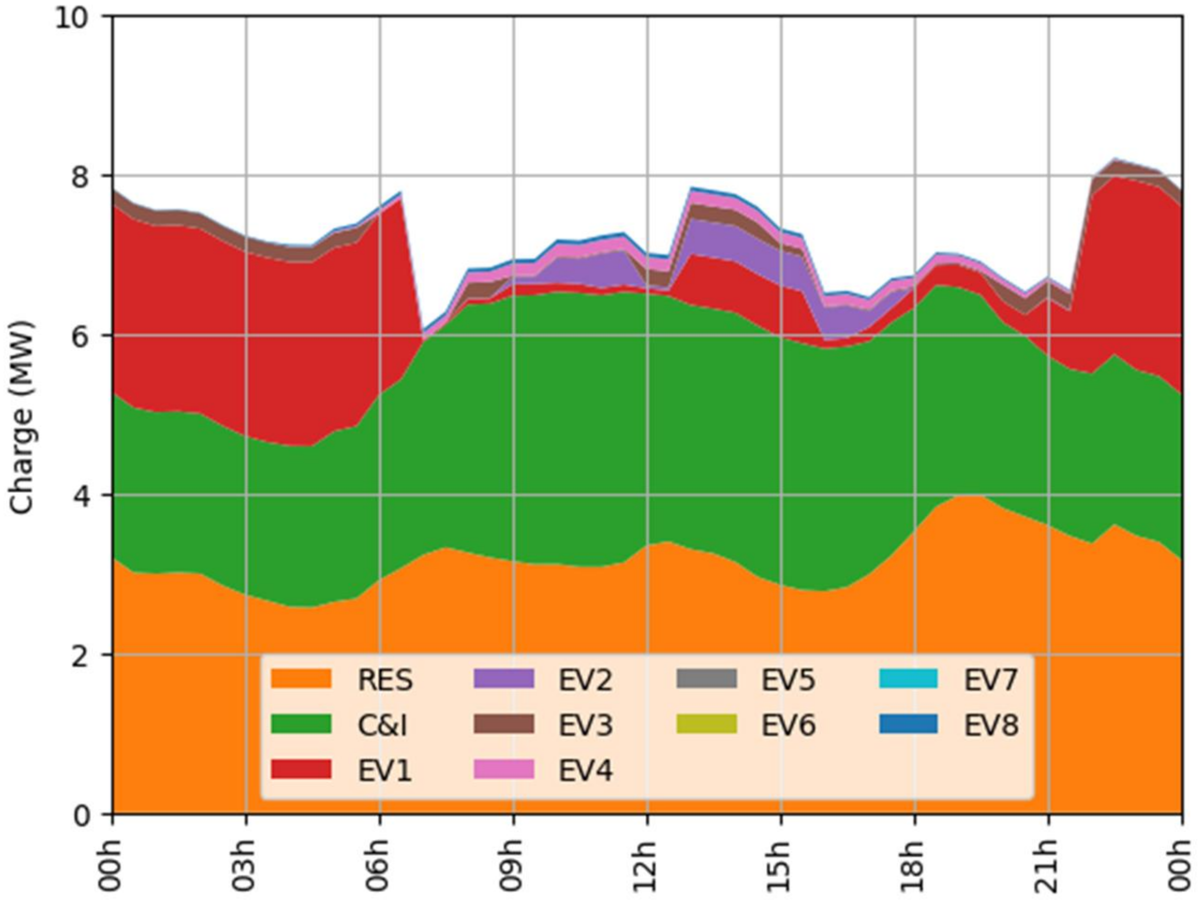
Appendix 1 : Residential area

Note : RES corresponds to residential consumption. C&I corresponds to commercial and industrial consumption

- Load curves in a residential area at the peak consumption in low flex and high flex scenarios.



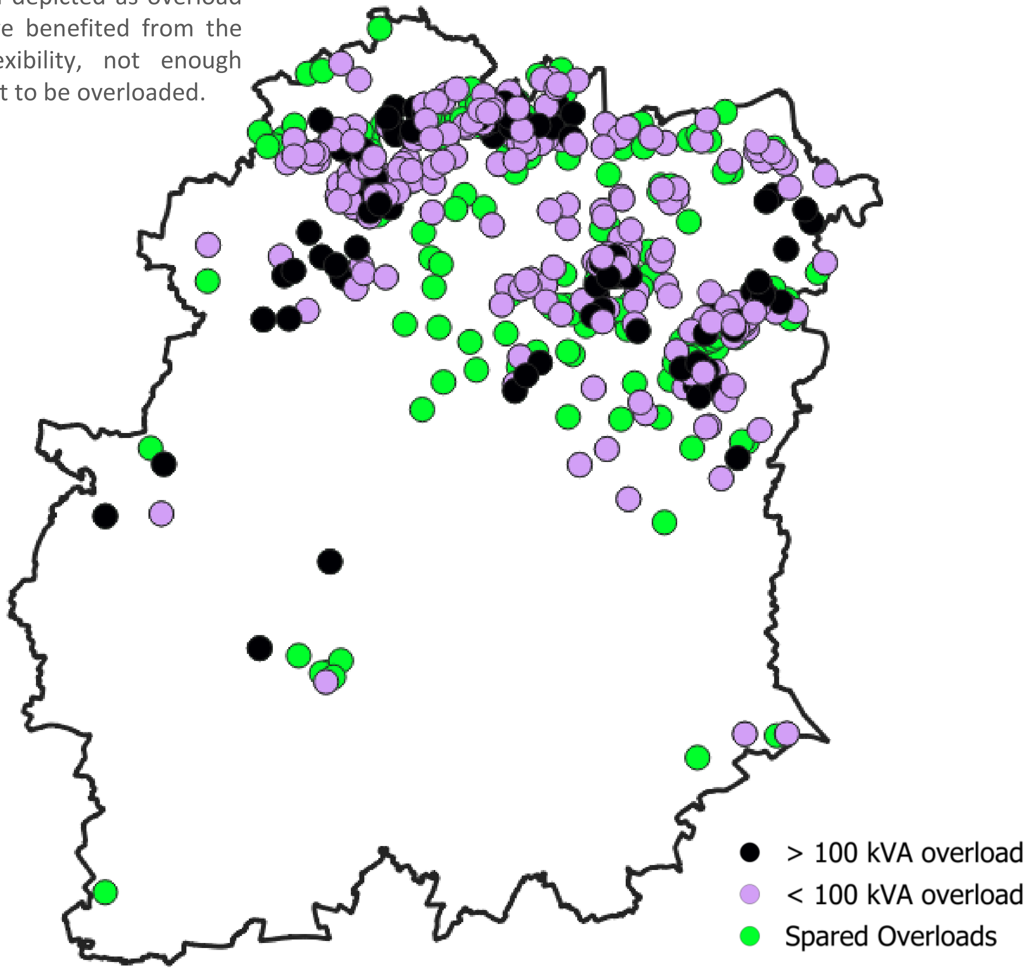
Low Flexibility scenario



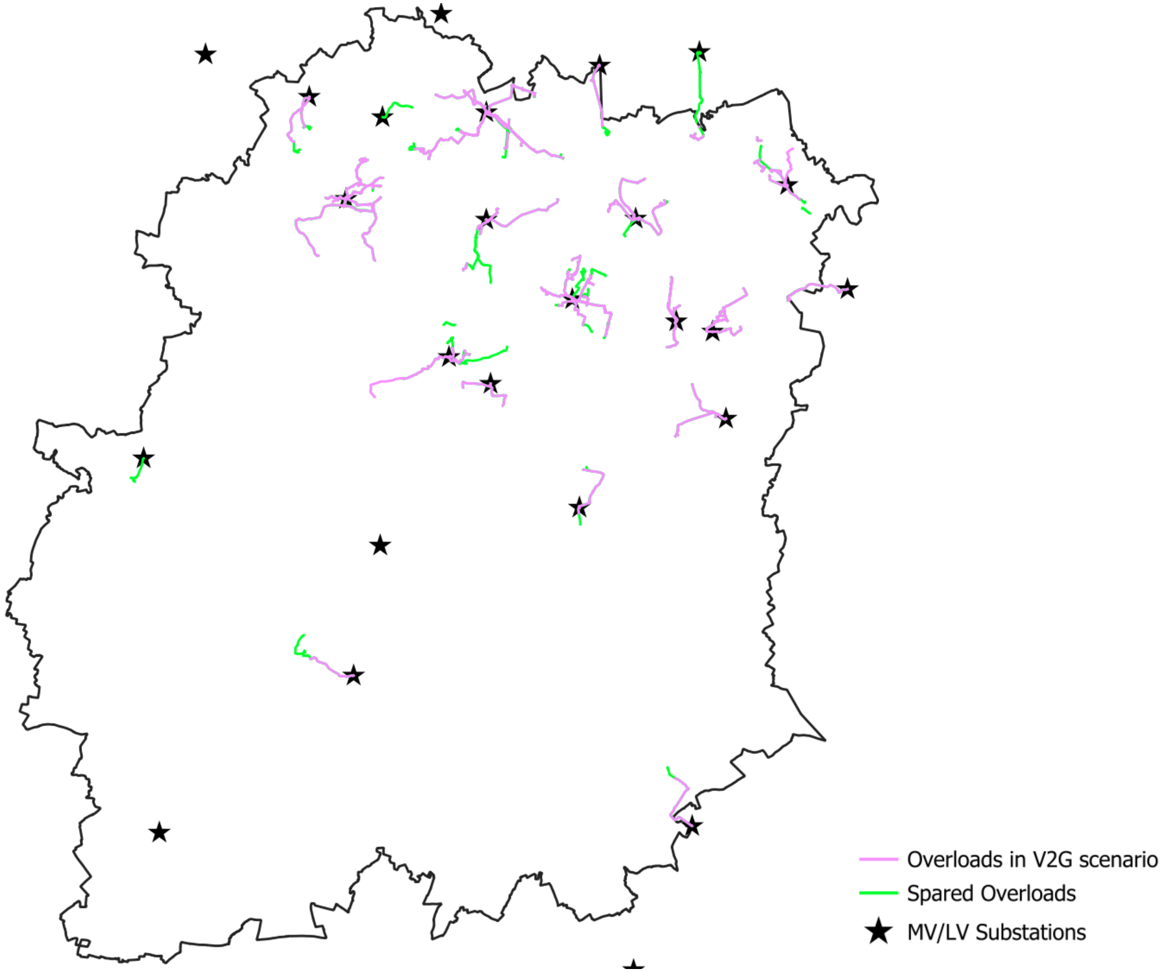
High Flexibility scenario

NB : « Spared Overloads » depicts transformers that are overloaded in one scenario, and not overloaded in the other. Assets still depicted as overload might have benefited from the higher flexibility, not enough though not to be overloaded.

Appendix 2 : *High Flex* Overload Maps



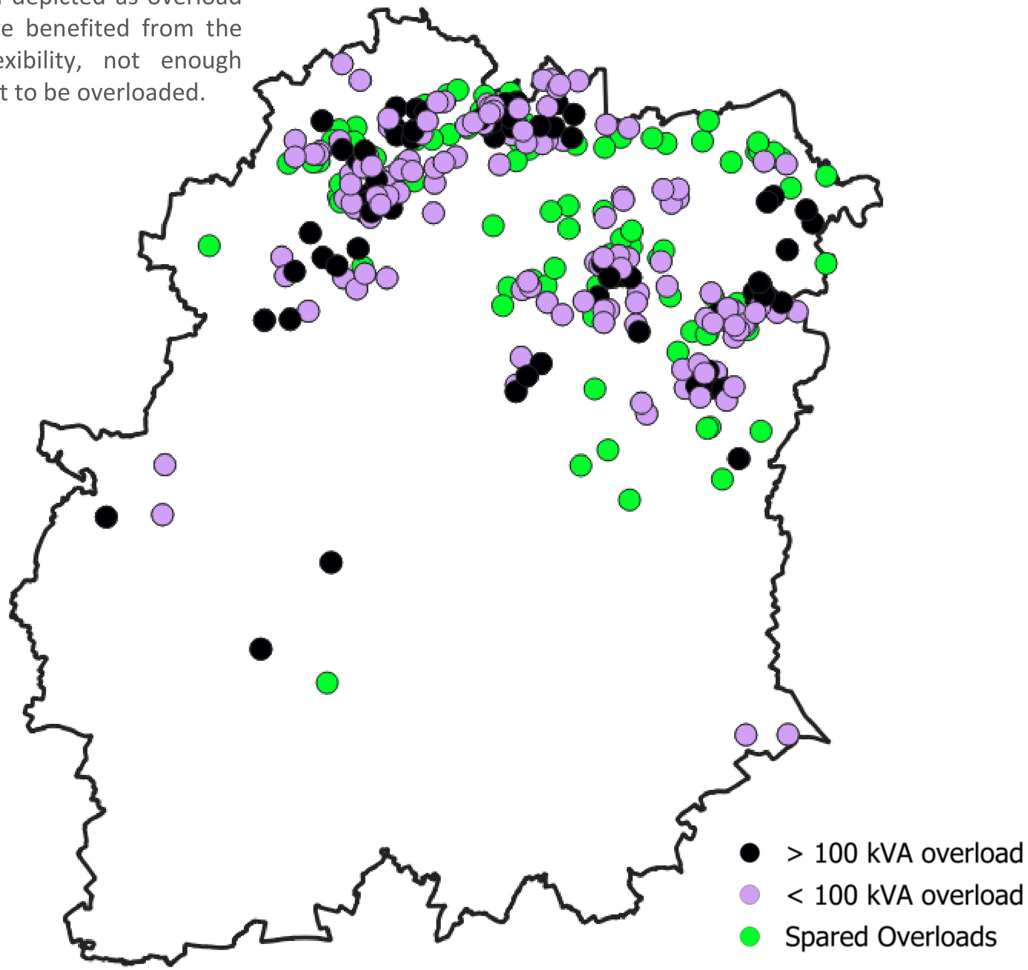
MV/LV substation overloads in the *High Flexibility* scenario, and spared overloads compared to the *Low Flexibility* scenario.



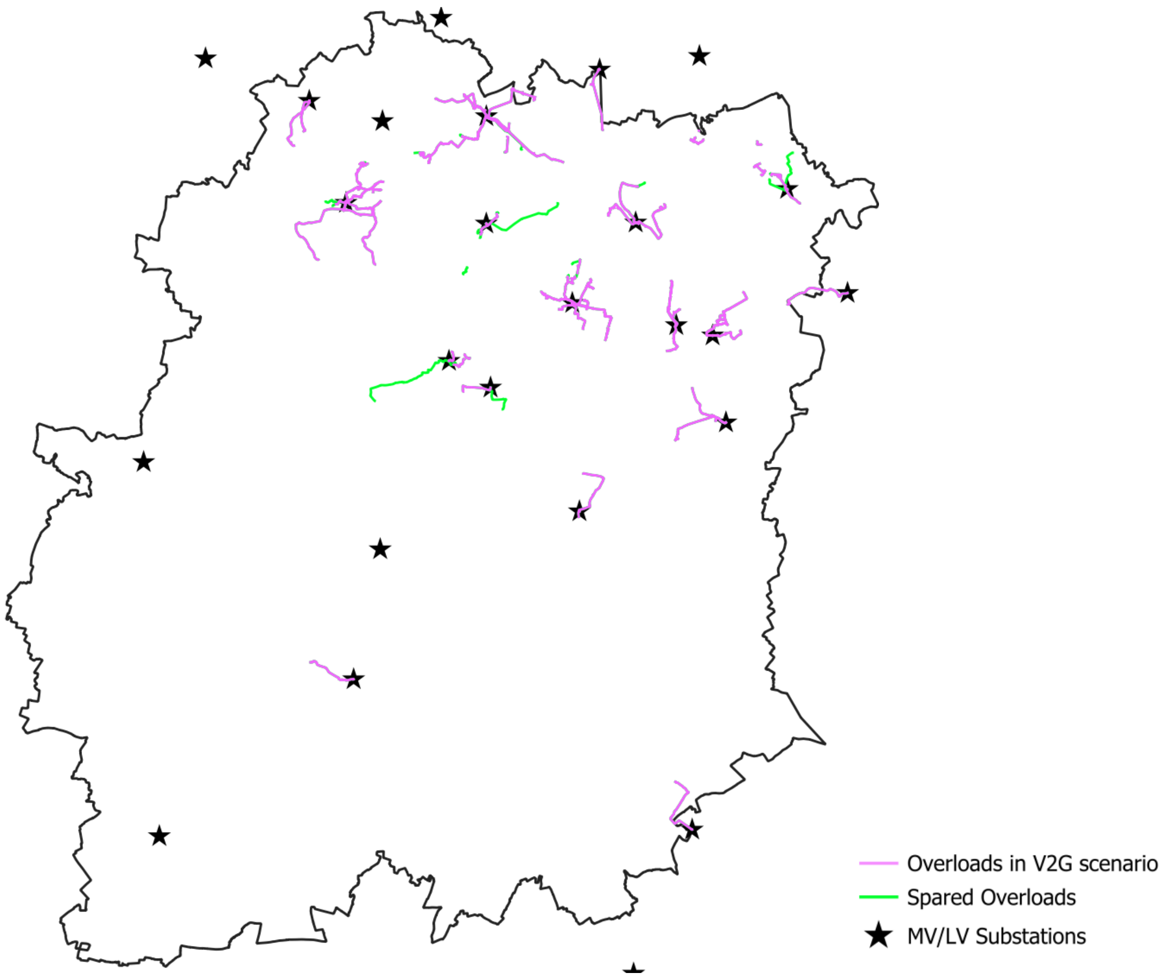
MV line overloads in the *High* scenario, and spared overloads compared to the *Low Flexibility* scenario.

NB : « Spared Overloads » depicts transformers that are overloaded in one scenario, and not overloaded in the other. Assets still depicted as overload might have benefited from the higher flexibility, not enough though not to be overloaded.

Appendix 3 : *V2G* Overload Maps

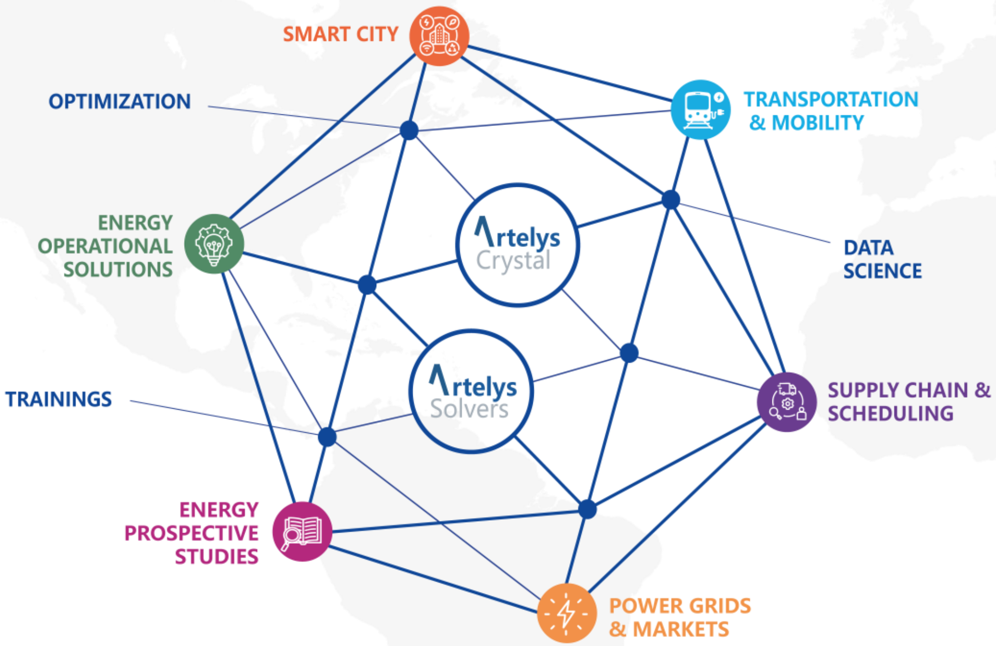


MV/LV substation overloads in the *V2G* scenario, and spared overloads compared to the *High Flexibility* scenario.



MV line overloads in the *V2G* scenario, and spared overloads compared to the *High Flexibility* scenario.

Contacts



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