G0401

Flexibility shares in a low-voltage distribution grid:
Identification of dimensioning load peaks and characterization of impacted end-customers for flexibility activation as a solution for peak mitigation

Teo Brigljevic (1), Jean-Philippe Bacher (2), Jean Hennebert (3)

(1) Groupe E SA, Rte de Morat 135, 1763 Granges-Paccot, Switzerland
Tel.: +41 26 352 55 83
teo.brigljevic@groupe-e.ch, teo.brigljevic@master.hes-so.ch

(2) ENERGY institute, HEIA-FR, HES-SO University of Applied Sciences and Arts Western Switzerland, Bld de Pérolles 80, 1700 Fribourg, Switzerland
jean-philippe.bacher@hefr.ch

(3) iCoSys institute, HEIA-FR, HES-SO University of Applied Sciences and Arts Western Switzerland, Bld de Pérolles 80, 1700 Fribourg, Switzerland
icosys@hefr.ch, jean.hennebert@hefr.ch

Abstract

Among the issues distribution system operators are anticipating today, the management of peak loads is at the forefront. This problematic has repercussions on the dimensioning of the network infrastructure that must support these peaks, consequence of the deployment of distribution energy resources like solar panels, or the introduction of future consumption needs driven by the electrification of the energy system. In answer to this problematic, leveraging the electrical flexibility of end-customers mixing consumption and production profiles is considered particularly promising to avoid the oversizing of the grid infrastructure or the use of dimensioning cases too strict for connecting new end-customers to the grid.
To determine the flexibility shares the DSOs can use as leeway for the grid management, the end-customers' load profiles made available by the deployment of advance metering infrastructure are leveraged, in combination with the data obtained from the DSOs' geographical and network information systems. Utilizing the deployment of their advance metering infrastructure, Groupe E initiated a data-driven project analyzing the load profiles in a typical low-voltage distribution grid covering 269 distinct end-customers. These end-customers present combinations of profiles mixing baseline residential consumption, particular non-standard consumption (heat pumps, electrical vehicles) and production (photovoltaic) profiles.
Based on this data, a methodology has been proposed to identify critical loci in time and location where the grid infrastructure reaches its load limits and targets select impacted end-customers for the activation of flexibility lowering in return the peaks critical for the infrastructure. The methodology follows a data-oriented approach to (1) identify the flexibility shares in the grid where the activation improves the load on the infrastructure using the load profiles and (2) propose a flexibility controlling strategy benefiting the grid infrastructure with the analysis of the effects of this strategy on the grid infrastructure and the impacted end-customers.

Keywords: electrical flexibility, low voltage distribution grid, advanced metering infrastructure, load profiles, time series

Introduction

With the expected growth of electrical energy consumption and the changes in power flow directionality in distribution grids, distribution system operators (DSOs) will be more and more confronted with the issue of peak consumption and production loads management. In Switzerland, the national final electrical consumption has stabilized with a +0.6% yearly average rate over the last 30 years with a total of 58TWh consumed in 2021 [1]. However, with the energetical electrification envisioned by the National Energy Strategy and recurrently mentioned by the strategy monitoring, DSOs foresee a rebound of electrical consumption for the coming years [2]. Existing signs of the changes in power flow directionality and electrification are seen today with the installation of new loads such as heat pumps (HP) and electrical vehicles (EV) or the growth of grid-connected solar production installations (PV).
When focusing on recently introduced loads impacting the peaks of power flow in the grid, the yearly rise of between +6% and +8% for HP since 2010 is observed, reaching 378’170 units for 1.4GW of combined electrical energy for [1], and between +30% and +40% for EV since 2010, reaching 70’223 cars in 2021 [3]. Moreover, looking at the evolution in grid-connected PV, a yearly rise between 11% and 28% in the number of installations is seen, for an average yearly rise of 7% in total installed power since 2012 reaching 476MW in 2020 with an average yearly rise of +23% of total energy generated reaching 2.6TWh in 2020 [4]. In either direction, consumption, or production, this new electrical power must somehow transit through the distribution grid, often requiring an upscaling of the infrastructure, especially at the low voltage (LV) level.
However, these new actors offer also new possibilities for their operation and controlling, with remotely interruptible devices that can be controlled by the DSOs or configurable consumption or production scheduling that can be uploaded and updated on the devices. Using these capabilities there is the opportunity to directly act on the end-customers’ loads impacting the occurrence of infrequent load peaks that would otherwise require an oversizing of the distribution grid infrastructure. The DSOs aims then to harness and leverage the end-customers’ flexibility with the objective of preventing load peaks by interrupting and shifting operable end-customers’ loads. The use of this flexibility must however satisfy the technical and social constraints of consumptions and productions in the grid: it is therefore necessary to determine when, where and how much flexibility is available. Similar studies assessing demand flexibility needs and opportunities have been conducted in the recent years by Leiva et al. [5] and Abgobanye et al. [6], showing promising results in activation of flexibility for the operating of distribution grids.
In this project, a method to determine these shares of flexibility in the distribution grid is proposed, using primary DSO-available GIS and NIS (geographical/network information system) data and end-customers’ load measurements obtained thanks to recently deployed advanced metering infrastructures (AMI) using smart meters. The chapters in this document cover the following steps: 1) Context, 2) Baseline analysis, 3) Results, 4) Future works, and Conclusion.

1. Context

As planned by the National Energy Strategy, the Swiss DSOs are rolling out the new AMI using smart meters, aiming for a minimum end-customers coverage of 80% by 2027 [7]. Leveraging the installation of this infrastructure as part of proof-of-concept tests by the western Switzerland DSO Groupe E conducted in 2021, a candidate LV distribution grid has been selected as suitable for flexibility shares analysis. This chapter describes both the attributes of this environment and the available data used for the project.

1.1 Environment description

The considered LV distribution grid consists of 164 unique service points, supplying 269 unique end-customers divided between 6 separated LV branches, all supplied at the same medium voltage (MV) to LV substation. Using the DSO GIS and NIS data, the service points are described as seen in table Tab.1. This composition shows that the distribution grid is of a highly residential nature, resonating with the flexibility objective of a granular control of the end-consumers' installations to optimize power flow to limit peaks. Moreover, looking at the distribution of controllable power loads, both for consumption like HP and EV and for production like PV, table Tab. 2 sums up the GIS and NIS data.
Both the “Villa” and the “Apartment block” categories are shown to offer sizable amounts of controllable devices, potentially useful for flexibility activation in the grid using HP and PV installations. Despite the EV category only represented by one single user, considering the very residential nature of the grid, the potential growth for EV can be assumed, especially for end-customers in by the “Villa” description.
As part of the AMI deployment, 256 of the 269 unique end-customers were equipped with individual smart meters. The metering coverage is shown in table Tab. 3. There are therefore thanks to the AMI unique load curves available with a 95% penetration rate for this distribution grid. Examples of a more detailed decomposition showing the distribution of HP, EV and PV per customer category is presented in section 3.2.

1.2 Categories of data sourced from the considered environment

Two main categories of data were used within this study: GIS/NIS data and AMI data. As already shown in part, detailed GIS and NIS data is available, informing not only on the characteristics of end-customers but also describing the entire topological construction of the LV grid infrastructure, from the MV to LV substation all the way down to individual service points. Figure Fig. 1 shows the reconstruction of the considered grid, indicating with coloration the 6 different LV branches supplying the end-customers.

Description	Villa	Apartment block	Farmhouse	Public infrastr.
Amount in #	157	5	4	3

Tab. 1 – Distribution of service points by unique categories

Description	Villa		Apartment block		Farmhouse		Public infrastr.	
Amount	*in kW*	*in #*	*in kW*	*in #*	*in kW*	*in #*	*in kW*	*in #*
HP	149	74	102	5	2	1	0	0
EV	17	1	0	0	0	0	0	0
PV	344	43	0	0	0	0	0	0

Tab. 2 – Penetration of consumption and production devices, in power volume and number of devices

End-customer category	**Amount in #**	**Amount equipped with AMI in #**
Villa	163	154
Apartment	71	69
General services (incl. heating)	18	16
Studio	8	8
Others	9	9
TOTAL	**269**	**256**

Tab. 3 – AMI coverage per end-customer category

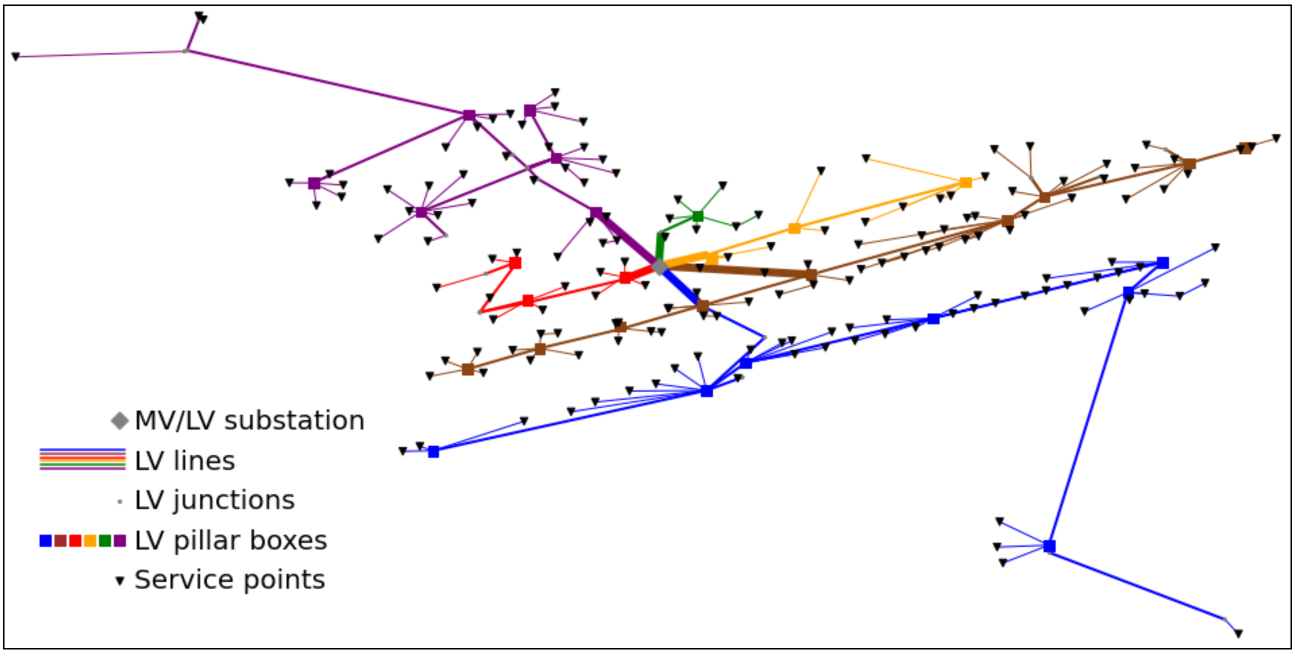

Fig. 1 – Graph representation of the considered distribution grid

Physical quantity	**Points of data**			
Voltage in V	UL1		UL2	UL3
Current in A	IL1		IL2	IL3
Power in kW, kvar	Pin	Pout	Qin	Qout

Tab. 4 – Points of data available per smart meter

The GIS and NIS data is primarily used for attributing the power loads measured with the AMI, identifying the end-customers' consumption and production and their potentially available devices for flexibility activation, and reaggregating the loads on the LV lines up-stream between the service points and the MV to LV substation. The analysis of these power loads is shown below in chapter 2.

The AMI data is available following the smart meters deployment, carried out over the second half of the year 2020. Time series measurements are therefore available for a complete year, taken from 04.01.2021 to 31.12.2021 with 15-minutes intervals, totaling 34'656 unique points of data expected for each of the 259 smart meters. For each metering device, table Tab. 4 shows the surveyed measurements. For each end-customer in the grid, it is therefore possible to follow both the bidirectional power loads measured at meter and the voltage evolution throughout the year.

2. Baseline analysis

This chapter presents the analysis of the AMI data combined with the GIS/NIS DSO data. These results give an overview of the various possibilities enabled by the availability of voltage and load curves coupled with the precise knowledge of a distribution grid composition and provide the baseline considerations used further for flexibility share identification and flexibility application.

2.1 Voltage measurements at the end-customers'

Using the 3-phase voltage measurements, it is possible to follow the voltage variation for each end-customer. For DSOs, this variation can be a problem to solve in both cases of consumption (voltage fall) and production (voltage rise), as the supplied voltage at the

end-customers' is regulated both by norms in application such as the DIN EN 50160 norm [8] and European-wide recommendation such as the D-A-CH-CZ document [9].
Following these rules, DSOs are for example required to guarantee a minimal and maximal voltage variation of ±10% measured at the end-customers'. Before the deployment of AMI, precise measurements closest to the end-customers in the grid could only be done using specialized devices on a per-case basis. Using the AMI, it is now possible to follow the voltage evolution without interruption for each equipped end-customer and perform analysis such as shown in figures Fig. 2 and Fig. 3.
Going back to the 34'656 unique points of data proposed in the previous chapter, the end-customers' voltage evolution in figures Fig. 2 and Fig. 3 show that portions of data are missing for single or multiple days intervals. These gaps are caused by malfunctioning of the AMI, occurring on the side of the metering devices and/or because of temporary downtime of the telecommunication infrastructure used for metering data upload, shortcomings caused by the proof-of-concept nature of the deployment test conducted by the DSO. "Purple spots" occurring seemingly stochastically over the year-range measuring interval are also noticeable, mainly attributed to metering device misreading.
Overall, with this first simple visualization, the following issues impacting the end-customers for the DSO to solve are seen:

1) fall of voltage during the winter season, more so in the middle of the night coinciding with the simultaneous turning on of heaters by telecontrolling[1], in the morning with the end-customers' waking up, and in the evening with the typical residential load.
2) rise of voltage during the summer season, in the middle of the day coinciding with the simultaneous distribution production coming from the PV installations.

These issues occur with the rise of power consumption and production respectively. It is therefore logical to infer that with a reduction of these power loads, if possible, using flexibility activation, voltage differentials will also decrease. The analysis of flexibility activation on the voltage evolution is discussed in more details in chapter 4.

[1]*The DSO Groupe E relies on centralized telecontrol of the residential heating infrastructure for turning on and off commands, carried through the grid infrastructure over a specific frequency. Historically, the turning on commands were set to occur simultaneously in the middle of the night to take advantage of lower energy prices on the energy market, but this practice is progressively leading to voltage drop issues and risks of overloading of the electrical grid infrastructure leading to oversizing of equipment to handle the peak loads.*

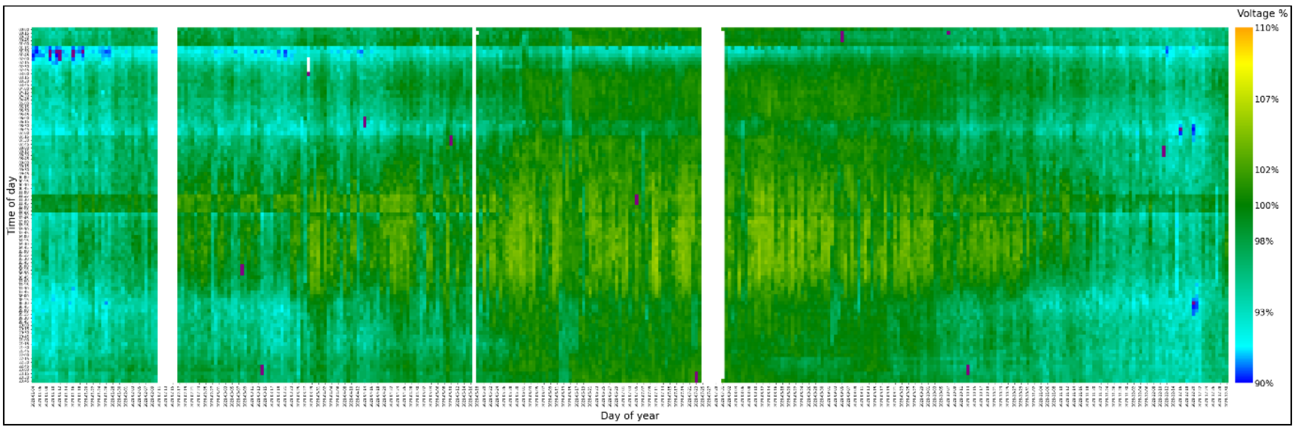

Fig. 2 – Calendar heatmap showing the voltage evolution for an end-customer affected by low voltage falls

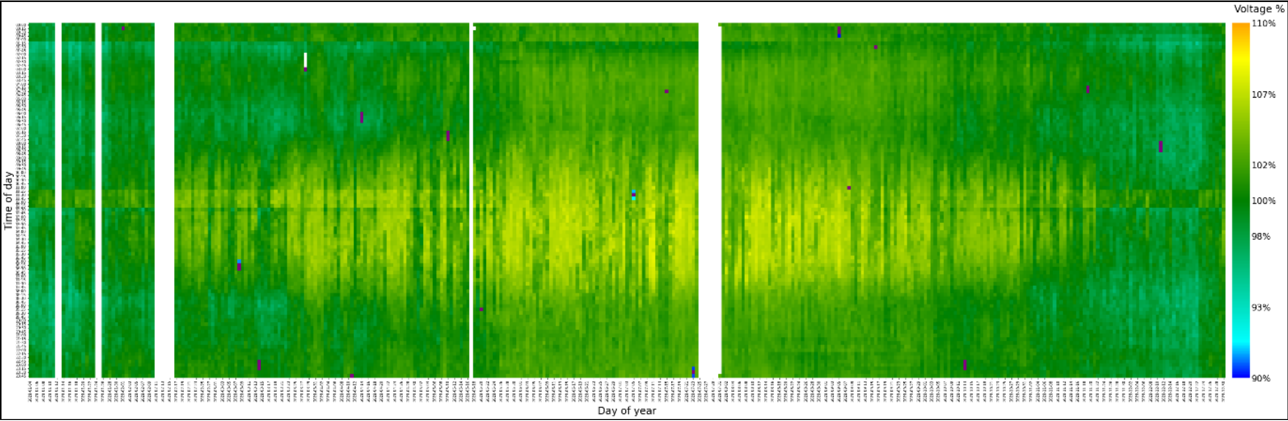

Fig. 3 – Calendar heatmap showing the voltage evolution for an end-customer affected by high voltage rises

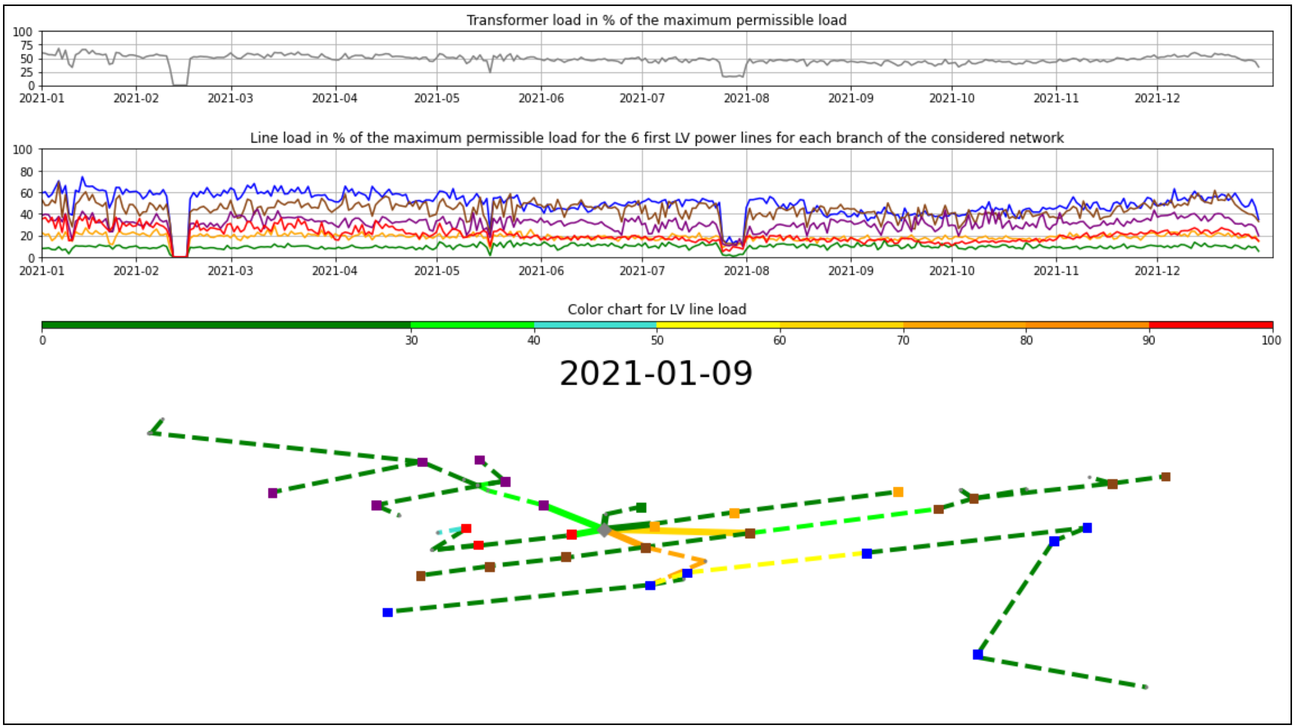

Fig. 4 – Evolution of the maximal measured load per line shown in the distribution grid and the aggregation of values at the MV to LV transformer

2.2 Topological reconstruction and load attribution

The other main consideration for the DSO is the load of the existing infrastructure, from the MV to LV transformer through the grid power lines and to the end-customers' connection line ("last mile"). Using the power measurements obtained from the AMI, these power loads are mapped to every single one of the 259 equipped end-customers. Then, using the GIS/NIS data, the distribution infrastructure is represented in the form of a topological graph where nodes match the MV to LV substation, LV pilar boxes, LV junctions and service points, and where edges match the LV power lines, as already shown in figure Fig. 1. Using additive backpropagation starting from the service points nodes and going up the LV lines, the corresponding loads per LV line are calculated, as shown in Eq. 1 and Eq. 2:

$$\text{Line topology}: \text{ Substation} \rightarrow \text{Line } j \rightarrow \text{PB } a \rightarrow \text{Connection line } i \rightarrow \text{Service point } i$$
$$\text{Power line } j \text{ load}: \text{ Sum of loads of service points } i \qquad \text{Eq. 1}$$

$$\text{Service point load: } \text{Load}_{\text{S,i}} = S_i = \sqrt{P_i^2 + Q_i^2}$$
$$\text{Power line load : } \text{Load}_{\text{I,j}} = I_j \text{ with } S_j = \sum(S_i) = I_j \cdot U_L \cdot 3 \qquad \text{Eq. 2}$$

After computing the individual loads per LV power line, and matching the values with the topological data, the load evolution across the grid over the year-range of available measures is compiled as shown in figure Fig. 4. Again, intervals with missing values are visible similar to what has been observer for figures Fig. 2 and Fig. 3. Nonetheless, some branches undergo higher typical and maximal loads than others, as demonstrated by the “blue” and the “brown” branches shown in figures Fig. 1 and Fig. 4. Based on these results, the next chapter presents a methodology to identify time specific and location specific peak load occurrences to be targeted by flexibility-based load management.

3. Results

Although not all of the objectives of the full “Flexibility Shares in a low-voltage distribution grid” study have been achieved at the time of preparation of this document, the first findings required for the project ambitions can already be discussed. This chapter goes over these results, expanding upon concepts discussed in previous chapters.

3.1 Identification of problematic loci: moment and location of occurrence

As discussed in section 2.2 and shown in figure Fig. 4, the load flows are known for each power line of the considered distribution grid. Using the bidimensional temporal and situational information, the next step calls for the identification of problematic loci where the infrastructure risks overloading. Despite having no critical situations in this grid, it is still possible to look for dimensioning cases, i.e., moments of maximal measured load per line. When focusing on the common grid infrastructure (excluding “last mile” connections), the occurrence of these dimensioning cases can be represented in a calendar map for the 65 remaining power lines as shown in figure Fig. 5.
Clear clusters emerge when looking at the distribution in figure Fig. 5, regrouping occurrences both by time range and by distribution grid branch. The corresponding loci can be determined both algorithmically by clustering analysis and visually by observation. Looking into select branches, these clusters appear more clearly, as shown in figure Fig. 6. Based the results displayed here, specific analysis has been done on the “blue” (Fig. 6a) and the “purple” (Fig. 6b) branches.

3.2 Flexibility identification by affected end-customers

Figure Fig. 7 shows the power lines considered as problematic from section 3.1. Unsurprisingly, both branches see the most charged connections on their principal distribution arteries, except for the first segment in the “purple” branch. For these two examples, a detailed description of affected end-customers is provided in table Tab. 5, in order to then identify the potential flexibility technical availability.
From the affected end-customers, the power measurements are then extracted from the AMI data for the relevant timeframes, split into the four categories shown in table Tab. 5 and finally summed per category. When displayed as a function of time, the results can be seen in Fig. 8. Looking at the power evolution, the following can be deduced:

a) The “blue” branch displays a significant peak occurring between 01:00 and 02:00 in the night of the considered interval, driven by the turning on of HP. Looking at the preceding and following hours, it appears that the devices contributing to this peak could have their power consumption distributed by activation of flexibility to smoothen the overall power consumption.

b) The “purple” branch displays its most significant consumption peak 19:00 and 22:00 of the considered interval, typical hours for residential activity. It is interesting to note that in the preceding hours, a peak of PV production can be seen. If the technical and social constraints allow for it, this case presents is promising for an activation of flexibility that could match part of the consumption demand with the production offer in time.

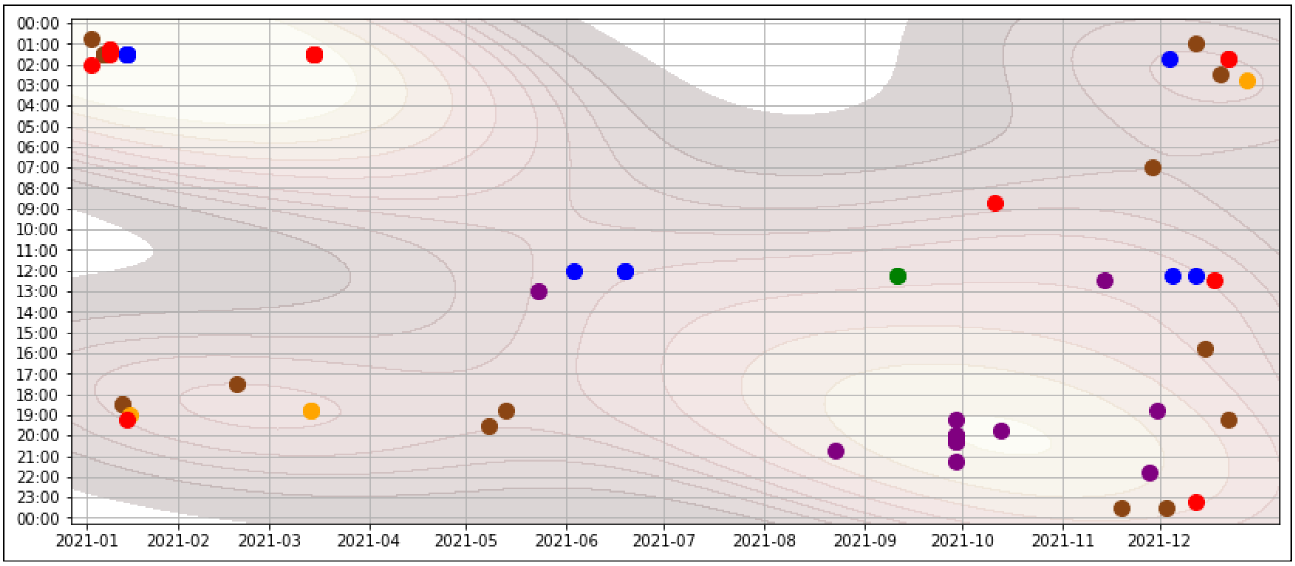

Fig. 5 – Distribution of dimensioning cases for the common grid infrastructure with branch coloration

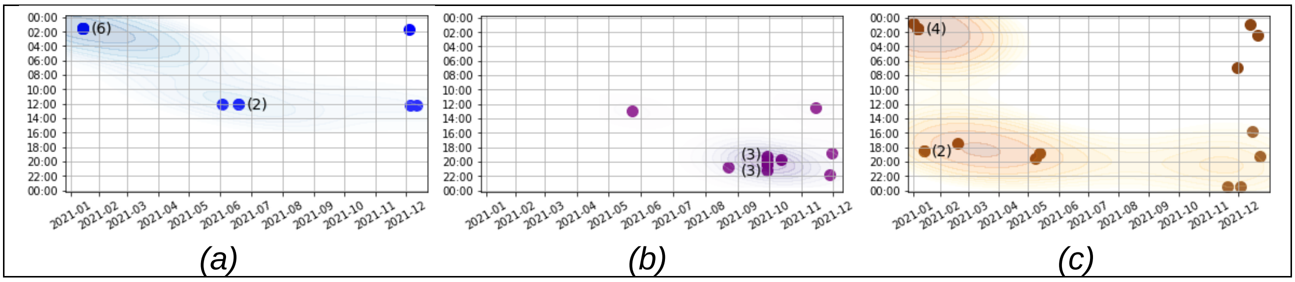

Fig. 6 – Distribution of dimensioning cases for the common grid infrastructure with branch coloration and indication of overlapping points

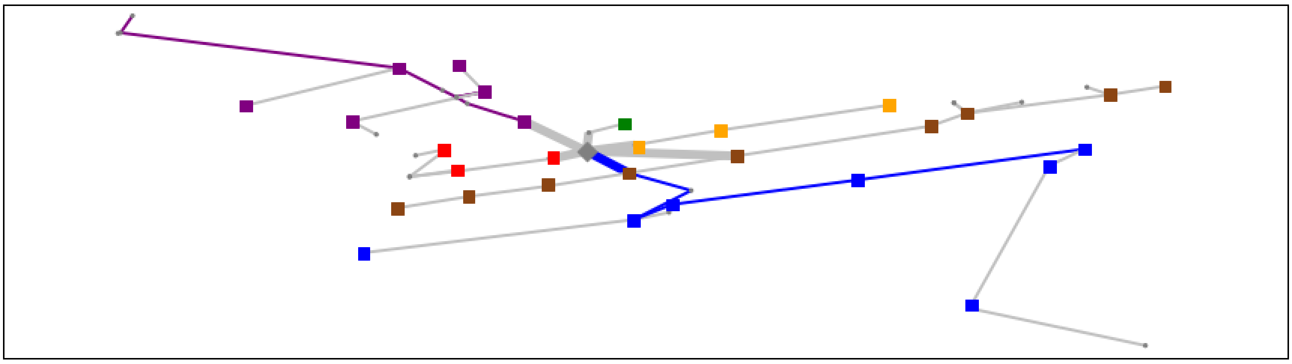

Fig. 7 – Topological graph showing the problematic lines for the considered (colored) and discarded (greyed out) branches

Description		"Standard"	w/ HP	w/ PV	w/ HP&PV	**Total**
Amount in # / %	**Blue**	39 / 52%	25 / 34%	5 / 7%	5 / 7%	**74**
	Purple	32 / 67%	8 / 17%	2 / 4%	6 / 12%	**48**

Tab. 5 – End-customers' characteristics and distribution over both branches

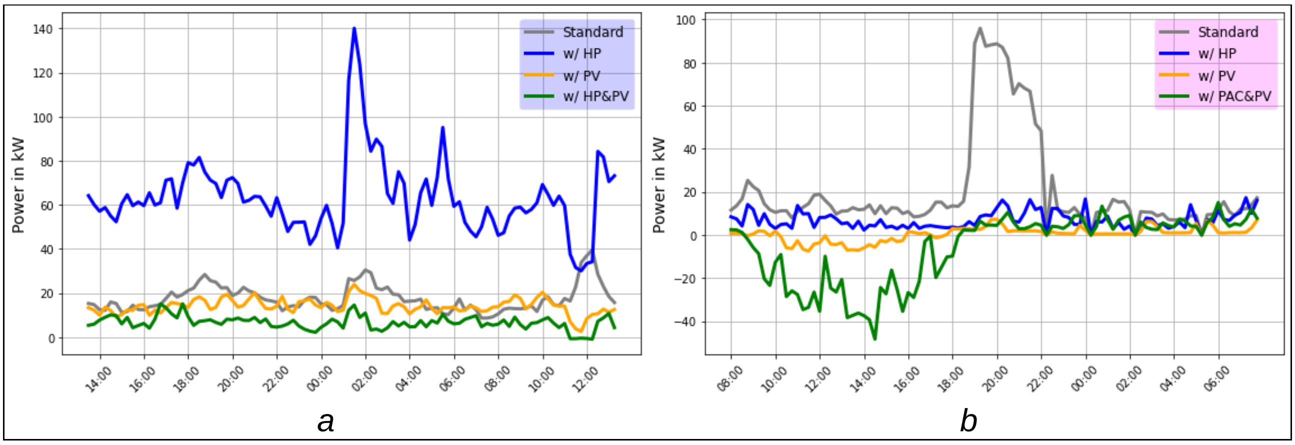

Fig. 8 – Power evolution centered around the dimensioning cases for the "blue" (a) and "purple" (b) branches, for dates 2021-01-16 and 2021-09-29 respectively

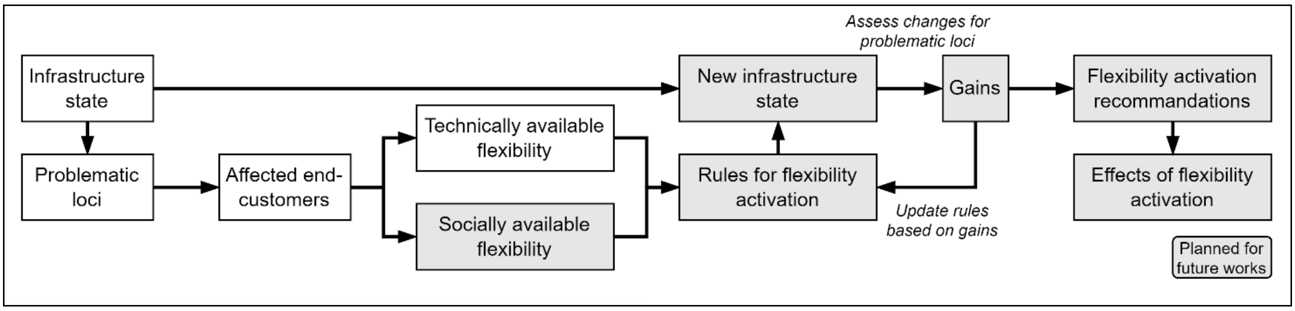

Fig. 9 – General flow diagram for the proposed methodology

3.3 Methodology proposal for assigning and activating flexibility

With the identification of problematic loci by LV line peak load analysis and the partitioning of impacted end-customers, the first steps for the complete envisioned methodology are in place. Figure Fig. 9 displays the general flow diagram of the methodology. The remaining steps are discussed in detail in chapter 4.
With this methodology, the end result will provide the DSO with operation commands in the form of recommendations to apply at select end-customers' installations, leveraging their potential flexibility as a tool for reducing peak loads observed in the distribution grid and optimal operation and use of the existing infrastructure.

4. Future works

This chapter details the remaining planned works for completing the study "Flexibility shares in a low-voltage distribution grid". The steps described below will finalize the proposed methodology following already available results already discussed.

1) **Assigning flexibility**: When defining the available flexibility per end-customer, it is essential to determine whether the impacted end-customers accept a role of active contribution using their consumption and/or production profiles. To help with this step, results from Yilmaz et al. [10] will be leveraged to assign social acceptability ratings per end-customer that will be then use when defining flexibility activation rules.

2) **Defining flexibility activation rules**: The previous steps defined the list of affected end-customers with power loads available for flexibility activation and accepting of this activation. Next, the rules for implementing this activation based on availability and needs will be defined. Several approaches are currently considered, utilizing stochastic and greedy algorithmic implementations to list the end-customers to target with flexibility activation commands. After each command, the effects will then be evaluated to again influence activation rules based on the results in a feedback loop model aiming to find to optimal commands for flexibility activation.
3) **Assessing the effects of flexibility activation**: At the end of the process, an assessment of the gains and consequences of flexibility remains to be done. The analysis of these effects encompasses for example in-depth study of load impact on grid infrastructure using the resulting load curves in grid simulation software to compute voltage evolution, financial estimating of differed energy exchanges caused by load displacement, or impact for the end-customers and their consumption habits.

Conclusion

Working with AMI and GIS/NIS data, the results in this study have shown the possibilities for load analysis and load peaks identification in a low distribution grid. Furthermore, when integrating end-customers descriptions, their respective contribution to the peaks can be broken down in categories with installations with flexibility activation potential. Using these results, the times and places where the flexibility activation would serve the distribution infrastructure by reducing the load peaks are identified, in combination with end-customers to potentially target to this activation.
In future works focusing on flexibility activation, the rules of activation and their effect on the infrastructure and end-customers will be studied with the objective to devise a complete methodology used by the DSO for optimal operation of the distribution grid.

References

[1] Bundesamt für Energie BFE, **Schweizerische Elektrizitätsstatistik 2021**, 2021

[2] Swiss Federal Office of Energy, **Energy Strategy 2050 - Monitoring Report 2021**, 2021

[3] Bundesamt für Statistik, **Strassenfahrzeuge - Bestand, Motorisierungsgrad**, *Bestand der Strassenfahrzeuge nach Fahrzeuggruppe und Fahrzeugart ab 1990*, 2021

[4] SwissSolar, **Statistik Sonnenergie**, *Teilstatistik der Schweizerischen Statistik der erneuerbaren Energien,* 2021

[5] LEIVA et al., **Data-driven flexibility prediction in low voltage power networks** in International Journal of Electrical Power and Energy Systems 123, 2020, p. 106242

[6] AGBONAYE et al., **Mapping demand flexibility: A spatio-temporal assessment of flexibility needs and response potential** in Applied Energy 295, 2021, p. 117015

[7] **Stromversorgungsverordnung StromVV RS 734.71**, *Kap. 5, Abschn. 4a, Art. 31e Einführung intelligenter Messsysteme*

[8] **DIN EN 50160:2020-11**, *Voltage characteristics of electricity supplied by public electricity networks*, 2020

[9] FNN & OEW & VSE & CSRES, **D-A-CH-CZ Technical Rules for the Assessment of Network Disturbances**, 3rd edition, 2021

[10] YILMAZ et al., **Analysis of demand-side response preferences regarding electricity tariffs and direct load control: Key finding from a Swiss survey** in Energy 212, 2020, p. 118712