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DiGriFlex

D1.2 Relative costs and benefits of operational and scheduling options for distribution grids

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Résumé

Ce rapport décrit la méthode utilisée pour déterminer la valeur relative de la flexibilité et présente les données obtenues sur la base d'études de cas dans le réseau de distribution de Suisse Romande. Les différents groupes de services (réglage, gestion des congestions, gestion de la tension et continuité du service) ont été introduits dans le livrable 1.1. Selon le service considéré et selon qu'il s'agit d'un usage en export ou local, la valeur relative du service est donnée par : i) le coût du renforcement du réseau équivalent, ii) le coût d'un transformateur de distribution à changement de prise ou iii) la valeur historique du service correspondant dans le réseau de transport. Les points ii) et iii) sont relativement simples : les chiffres ont été recueillis en tenant compte des coûts historiques pertinents. La nouveauté de l'approche est toutefois concentrée dans le point i), la valeur relative du renforcement du réseau évité. Une valeur moyenne ex ante de cette valeur relative pour la flexibilité a été déterminée en considérant un grand nombre de renforcements de réseau possibles dans deux zones de réseau (rurale et urbaine) et en calculant ensuite un coût moyen du renforcement pour chaque kWh qui pourrait être injecté en plus dans le système. La valeur relative de la flexibilité est obtenue en actualisant le coût des renforcements dans l'ensemble de la zone de grille et en calculant une moyenne adéquate.

Summary

This deliverable describes the method used to determine the relative value of flexibility and presents the data obtained based on case studies in the western Switzerland distribution network. The different service groups (balancing, congestion management, voltage management and service continuity) have been introduced in deliverable 1.1. Depending on which service is considered and whether export or local use is considered, the relative value of the service is given by: i) the cost of the equivalent network reinforcement, ii) the cost of a tap changer distribution transformer or iii) the historical value of the corresponding service in the transmission grid. Items ii) and iii) are relatively straightforward: figures have been collected by considering the relevant historical costs. The novelty of the approach is however concentrated in item i), the relative value of the network reinforcement avoided. An ex ante average value of this relative value for flexibility has been determined by considering a big number of possible network reinforcements within two grid areas (rural and urban) and then computing an average cost of the reinforcement for each kWh that could be additionally injected into the system. The relative value of the flexibility is obtained by discounting the cost for the reinforcements in the entire grid area and computing an adequate average.

Acronyms

aFRR	Automatic frequency restoration reserve
DSO	Distribution System Operator
GIS	Geographic information system
LV	Low Voltage
mFRR	Manual frequency restoration reserve
MV	Medium Voltage
QDS	Quasi dynamic simulation
RMS	Root mean square
SCCER FURIES	Swiss competence centre on energy research – Shaping the future Swiss electrical infrastructure

Contents

1 Introduction

1.1 DiGriFlex project description

The Digriflex project aims at validating effective forecasting and optimal control algorithms for LV distribution grids. Two high-level objectives are formulated in the project proposal:

1. "develop effective forecasting and optimal control methods to ensure efficient and secure operation of distribution grids, as well as flexibility and ancillary service provision from local low voltage distribution grids to the upstream medium/high voltage grids, under uncertainties"
2. "implement the above forecasting and optimal control methods in a test case low voltage distribution grid"

The general approach in this project is to combine two layers of optimisation: in the prescheduling step, an optimal point of operation for all controllable resources is identified. The real-time optimisation then reduces the deviation between the scheduled and effective outputs of the considered resources.

1.2 WP1 description

WP1 "Definition of the ancillary services to be considered by the distribution system operator" delivers the list of considered ancillary services and their relative value compared to conventional approaches (typically reinforcements of grids or use of centralised ancillary services, e.g.). WP1 consists of two tasks:

- Task 1.1: Definition of services and degrees of freedom
- Task 1.2: Analysis and characterisation of available operational and scheduling options

At the end of WP1, the relative value of flexibility in LV distribution grids will have been determined based on several LV networks obtained from Romande Energie, component cost information obtained from DSOs and VSE and historical data for ancillary services in the Swiss transmission system published by Swissgrid.

1.3 Deliverables D1.1 and D1.2 scope

In deliverable D1.1 "Description of ancillary services provided within and from distribution grids, taken from literature and DSO experiences", the result of the selection of relevant ancillary services has been presented. In particular, ancillary services have been classified into three service groups (balancing, congestion management, voltage management and service continuity). A method for determining the relative value of each of these service groups either for local use or for export has been identified.

In this deliverable D1.2, the cost data for each of these items as well as the necessary network simulations is presented. The central part is the determination of the relative network reinforcement cost for each balancing service group previously identified. At the end of the report, the cost for each service to be used in the remaining parts of the project are summarised in a table (chapter 5).

2 WP1 organisation

2.1 Project plan

Based on the breakdown of activities presented in deliverable D1.1, the time plan of WP1 shown in Figure 1 has been established and updated. Compared to the time planning in the proposal, the paralleling of WP1 and other WPs has been agreed in order to accommodate the resource availability of several partners.

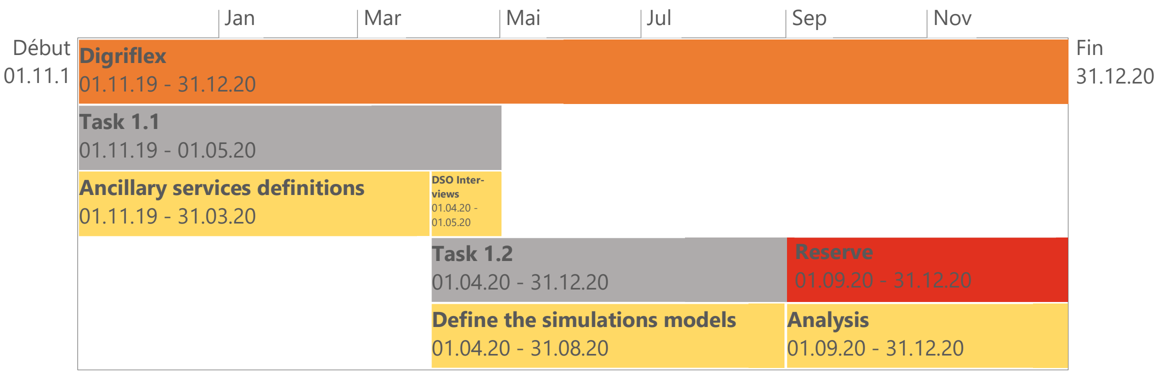

Figure 1: Summary of WP1 time plan

2.2 Tasks description

Figure 2 shows the activities for the WP1 tasks as well as an approximate effort repartition among the subtasks identified for the main partner of this work package, HEIA-FR. The contribution of all other partners is evenly split across the subtasks as it will mainly consist of interfacing and consulting on some specific questions. Several online meetings have been held for this purpose.

Task 1.1 is reviewing existing facts, knowledge and practices in order to integrate those into the DiGriFlex project. In a first step the established definitions of ancillary services have be analysed and expanded towards not yet implemented definitions for local use of similar ancillary service products. Proposals for more and novel ancillary services have been gathered from the literature. The comparison basis for the value of local services based on resource flexibility is network reinforcement. The initial data will be the established standardised costs of VSE/AES [1], combined with anonymised case examples provided by some of the interview partners (see report D1.1 [2]).

In task 1.2, the steps required to establish the relative value of avoided network reinforcement are implemented. Two grid areas were selected and modelled in a power systems simulation program. Based on hosting capability simulations, the reinforcement needed for additional PV generation (or load increases) was computed and its cost evaluated. In parallel, the additional energy injected (or drawn) into (or from) the grid was computed using an annual power flow simulation. By combining the two calculations, the cost associated with the injection or consumption of each additional kWh was determined. Its weighted average represents the relative value of the flexibility considered in this project.

Task 1.1	**01.11.2019**	**01.05.2020**
Ancillary services definitions	**01.11.2019**	**31.03.2020**
Literature study		
Define ancillary services and actors for local export and costs evaluation		
Define ancillary services and actors for upstream use and costs evaluation		
Define alternative solutions and evaluate the costs		
Preliminary cost comparison of alternative solutions		
DSO Interviews	**01.04.2020**	**01.05.2020**
Define interview questions based on the ancillary services definition research		
Contact the DSOs and meetings		
Task 1.2	**01.04.2020**	**31.12.2020**
Define the simulations models	**01.04.2020**	**31.08.2020**
Choose a network (real from RE or Relne)		
Set up the simulation for the reinforcement calculation		
Set up simulations for the flexible energy calculation		
Set up simulations on a different network		
Analysis	**01.09.2020**	**31.12.2020**
Run simulations and validate results		
Formulate the flexibility valuation (necessity/cost)		
Reserve	**01.09.2020**	**31.12.2020**

Figure 2: Effort breakdown per subtask in work package 1 (HEIA-FR contribution).

2.3 Research method

Figure 3 shows the method adopted in the WP1 tasks described above. The literature review started with a keyword search in established databases. The information gathered in the paper was then organised and compared in tables discussed within the next sections of this report. The candidate services were then selected qualitatively by the experts of each partner represented in WP1 to obtain a shortlist of services considered: one group for export into higher network levels and another group of services for local use within the LV network. These two elements are combined with the first part of the DSO interview results to form the inputs into deliverable D1.1. The interviews were conducted in person, based on a pre-established questionnaire considering the needs of the project, but with the flexibility to explore other areas if the interviewee felt this was appropriate.

Activities for task 1.2 started with the establishment of simulation models of suitable LV networks. The basis for these models was provided by SCCER FURIES related activities where a method for the import of data from the GIS database into a state-of-the-art power systems analysis tool (PowerFactory in this case) had been established. The coverage and degree of detail of the data imported was expanded for the needs of this project: the consumption data measured on the MV side was broken down into LV consumer profiles approximated using published load profile generators in a manner that the aggregated net consumption corresponds to the measurements. The networks are used in order to assess the need for network reinforcements if the penetration of solar PV generation (or additional load) is increased in a randomised manner. Using power flow calculations, the cost of upgrading cables and other components in case of capacity or voltage variation violations are used in order to determine the value of the flexibility that would avoid the need for such reinforcement. Two approaches for the determination of the network reinforcement costs have been combined: standard costs published by VSE have been combined with confidential information obtained from several DSOs for specific projects. The result is a set of aggregated fitted cost curves.

The average value of flexibility has been determined by comparison with the annual costs of the equivalent network reinforcement. For the export of services, methods from other SCCER FURIES activities related to average values of services have been used and the results have been adapted and summarised in this report.

Figure 3: Organisation of activities in WP1 (orange: Task 1.1, green: Task 1.2)

3 Flexibility relative value definition

3.1 Local services

Table 1 shows the service groups identified in deliverable D1.1 and the method used to determine the relative value of flexibility, used either for local purposes (congestion and voltage limit overrunning in the LV network) or export into higher network levels.

Service Group	Benefits for interconnected system	Relative value evaluation	Local benefits	Relative value evaluation
Balancing	Reduce power demand	*Historical mFRR value* *→ § 3.2.1*	Reduce transformer load Peak shaving	*Cost of network reinforcement (line or transformer) if any is required* *→ § 3.1.1*
Voltage control	Support voltage plan	*Only relevant for NL1: tariffs according to Swissgrid voltage management* [3][1].	Voltage level maintained	*Cost of tap/changing transformer* *→ § 3.1.2*
Congestion management	Reduce power demand	Cost of network reinforcement (line or transformer) or *historical mFRR value*[2] *→ § 3.2.1*	No lines overload Transformers can be discharged Reduce outages Peak shaving Voltage is maintained in limits	*Cost of network reinforcement (line or transformer)* *→ § 3.1.1*
Continuity of service	Support system black start capability	(no relative value since the approach is new)	Consumer supplied in fault cases SAIDI/SAIFI improved	(no relative value since the approach is new)

Table 1: Benefits and relative value determination for local services from D1.1 [2]

The next paragraphs will introduce the methods, data and results for the evaluation of the value for each service group according to the method identified in deliverable D1.1. The table contains a reference to the paragraph corresponding to each service group investigated in this WP.

[1] In this project this will not be considered: a voltage plan would be needed for the transmission grid. Alternatively, the nominal voltage could be used. This would however require to have a network model for the upstream network, including the load flows, which is not realistic for this study. A simplified average tariff method will be applied.

[2] The approach depends on market design choices. The method for evaluating the cost of reinforcements is essentially the same as for local services. The equipment costs are different in higher voltage levels. However, the approach using mFRR prices is closer to recent evolutions suggesting that re-dispatch will be done using standard products in the future [4]

3.1.1 Calculation method for network reinforcement-based value

As described above, the novelty of the proposed approach is the determination of the flexibility value by comparing the use of flexibility with an equivalent network reinforcement, i.e. the reinforcement needed in case the flexibility cannot be used to maintain the network within its operation limits. The main steps for the process of determining this relative value are described in the Figure 4.

The basis for the calculation is an MV network (or several networks) with several MV/LV transformer stations and the model of each LV network including the position of loads and (PV) generators. First, the hosting capacity for additional distributed (PV) generators is calculated in order to determine how much additional generation could be accommodated in the considered grid at locations deemed critical (i.e. in general the end of branches). The same calculation is done with respect to additional load. The hosting capacity is defined as found in [5]:"Hosting capacity is generally defined as the amount of new generation or consumption that can be connected to the grid without violation of system constraints (e.g. power quality for connected customers) and without any network expansion."

Second, load and generation are added randomly in excess of the initial hosting capacity, as described in more details in chapter 4. This implies a need to reinforce the grid. The elements needing reinforcement and their cost are determined.

Third, the hosting capacity of the reinforced grid is determined. This is in general more than the newly added load or generation, since reinforcement is a stepwise process where the increments in capacity are much higher than the size of individually added loads or generators.

Fourth, an annual power flow simulation is carried out for the reinforced grid with the additional load or generation. The additional power transfers that are possible thanks to the network reinforcement are identified (details see chapter 4) and the corresponding annual energy is identified.

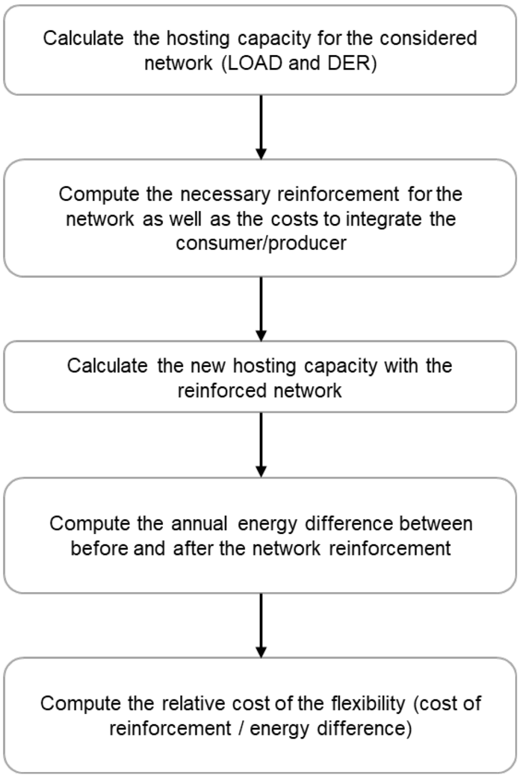

Figure 4 Calculation idea for the flexibility relative value

Fifth and finally, the annual cost of the network reinforcement is divided by the annual energy to determine the value of each unit of flexibility. This is first done for each considered LV network and subsequently an average value for the entire considered grid area is computed.

These calculations are implemented using DIGSilent PowerFactory and Python on two different grid areas (rural and urban). A more detailed explanation on how and where these simulations are implemented can be found in chapter 4, along with the quantitative results. The details of the standard costs, used for reinforcement cost calculation, can be found in paragraph 3.1.3.

The cost of the network reinforcement for the additional load flow in the grid corresponds to the annual costs of the reinforcement. These annual costs will be considered as an annuity [6] corresponding to the initial investment c_{tr} respectively c_{cable}. n is the (accounted) lifetime of the asset considered and the discount rate r corresponds to the difference between the cost of capital (WACC) and the expected annual increase of electricity prices i_{EP}: r = WACC – i_{EP} (for WACC not equal to i_{EP}). In the following, an annual increase of electricity prices will be disregarded. The cost comparison for each kWh of additional energy (that could be avoided using flexibility) is the ratio between these annual reinforcement costs and the annual amount of additional energy that would flow if the reinforcement was effectively implemented.

The resulting annual costs for each cable or transformer replaced during the network reinforcement are:

$$c_{tr[1y]} = c_{tr} \frac{r}{1-\left(\frac{1}{(1+r)^n}\right)} \tag{1}$$

$$c_{cable[1y]} = c_{cable} \frac{r}{1-\left(\frac{1}{(1+r)^n}\right)} \tag{2}$$

With:

- r = WACC (weighted average cost of Elcom, 2017-2021), 3.83% [7]
- n = 40 years

These calculations have to be applied to each transformer and cable to substitute. The total costs for each LV network are a sum of several elements for the reinforcement. Using these results, the relative cost can be calculated.

$$c_{relative} = \frac{c_{tr[1y]}}{\Delta\, E_{tr}} + \frac{c_{cable[1y]}}{\Delta E_{cable}} \tag{3}$$

The additional energy which can be drawn or injected needs to be defined. Two definitions of the additional energy ΔE have been compared in order to calculate the relative value of the flexible energy. Figure 5 show the first definition, i.e. the total additional energy transiting through the considered LV network obtained by comparing the load curves before and after the addition of the load and generation. Here, ΔE is the total difference between the energy before (E_1(t)) and after (E_2(t)) the network reinforcement (represented by the orange part of the graph in Figure 5).

$$\Delta E = E_2(t) - E_1(t) = P_2(t) \cdot t - P_1(t) \cdot t \tag{4}$$

In order to evaluate different rates of utilisation of the flexible energy, a utilisation factor (uf) will be applied to the above formula. This is the second approach.

$$\Delta E = (E_2(t) - E_1(t)) \cdot uf \tag{5}$$

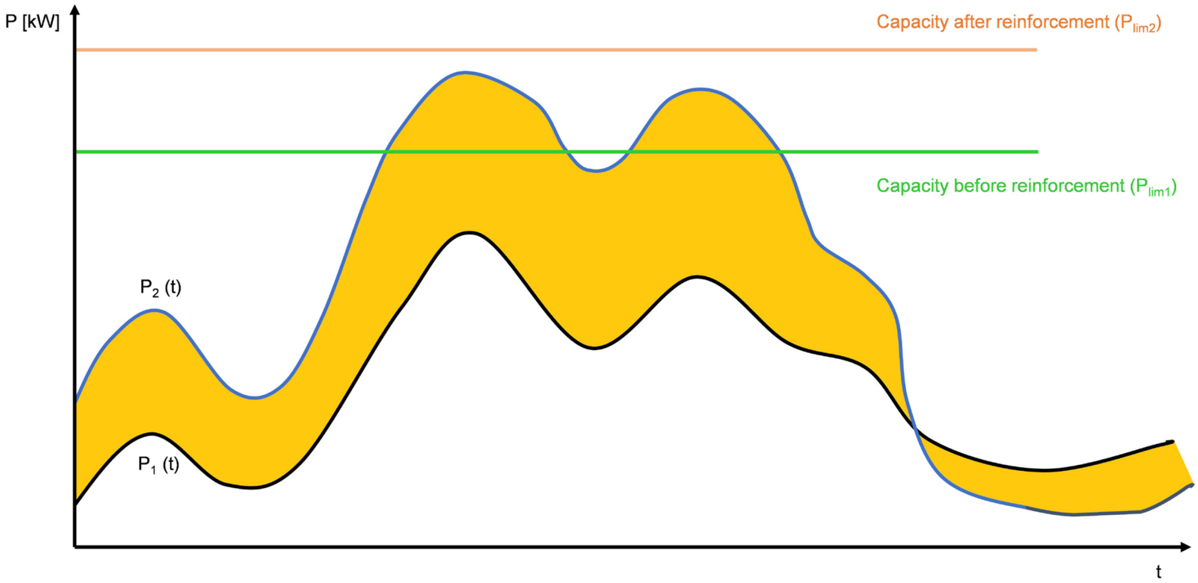

Figure 5 Representation of the total energy difference based on the total energy produced or consumed by the additional generation or load.

Figure 6 shows the second definition which uses the difference between the capacity of the LV network before the reinforcement and the loading of the network after the addition of new load and generation, taking into account that the added load and generation could be accommodated by the initial capacity for at least part of the time. After comparison of the initial results, the decision was made to use the definition according to Figure 6 for use in the DiGriFlex project: the energy effectively exceeding the initial capacity is the real driver for the network reinforcement cost, therefore it also represents the share of the energy that carries a relative value in case it can be reduced by using flexibility in the LV system. The energy transiting in the LV network (i.e. flowing through the MV/LV transformer) when the power is above the hosting capacity level before the reinforcement represent the variable ΔE (represented by the violet part of the graph in Figure 6).

$$\Delta E = \begin{cases} P_2(t) \cdot t, & P_2(t) > P_{lim1} \\ & 0 \end{cases} \tag{6}$$

This value represents the amount of the additional energy drawn or injected in the network thanks to the reinforcement, so the energy attributable to the reinforcement costs. The results can be found in chapters 4 and 5.

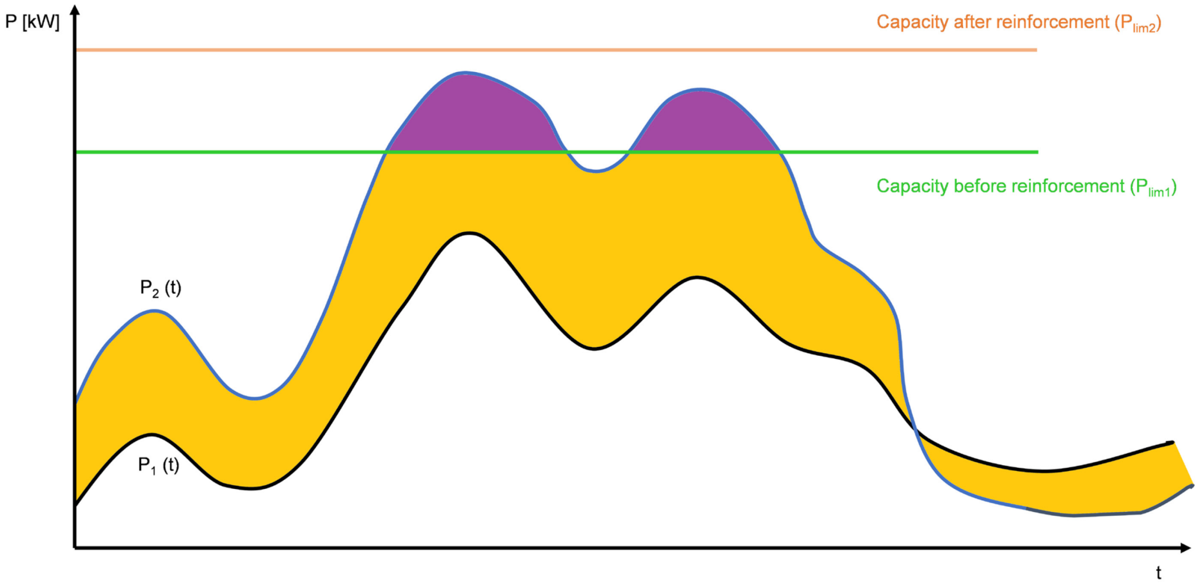

Figure 6 Representation of the above the total energy difference based on the total energy exceeding the LV network's total capacity before the reinforcement

3.1.2 Calculation method for tap changer transformer-based value

The relative value of reactive power for local voltage control is determined based on the cost of an on-load tap changer (OLTC) transformer. As shown in Table 2, such a transformer will have a higher cost than a standard transformer. Based on the same lifetime and discount rate as other network reinforcements discussed previously in this report, an annual cost is determined. The yearly useful kVArh for voltage control is based on the estimation that voltage control by an OLTC transformer would be required 2 hours per day on average during which the reactive power would represent 10% of the transformer's nominal power.

The average value given in the results summary at the end of this report is a weighted average of the values determined for each transformer size.

App. power	kVA	100	160	250	400	630	1000	1250	1600
Min. investment cost	CHF	14915.25	17770.03	21908.54	24429.22	28000.82	33775	36070.81	39284.95
Max. investment Cost	CHF	25510.08	26061.08	26887.57	28423.03	37481.98	49692.99	56294.48	63302.15
Annual Min. Cost	CHF	735	875	1'079	1'203	1'379	1'664	1'777	1'935
Annual Max. Cost	CHF	1'256	1'284	1'324	1'400	1'846	2'448	2'773	3'118
Yearly kVArh	kVArh	7'300	11'680	18'250	29'200	45'990	73'000	91'250	116'800
Value per kVArh Min	ct/kVar	10.1	7.5	5.9	4.1	3.0	2.3	1.9	1.7
Value per kVArh Max	ct/kVar	17.2	11.0	7.3	4.8	4.0	3.4	3.0	2.7

Table 2: Estimation of the value of reactive power based on the cost of an equivalent on-load tap changer transformer.

3.1.3 Description of the cost information used

The estimated costs for the equipment used for network reinforcements is based on three standard cost sources:

- Standard costs published by VSE [1]
- Groupe-e provided functions for cost evaluations of lines, cables and transformers replacement
- Project example from Romande Energie for an MV/LV station replacement

Data from these sources has been compiled into a set of fitted cost curves including a variation range. The data has been aggregated in a manner that makes the original input invisible, as required by the DSOs that provided the data. Cost functions were developed for the following cost items:

- Copper conductor (CU) cables replacement cost in function of the length and the conductor cross-section
- Aluminium conductor (AL) cables replacement cost in function of the length and the conductor cross-section
- Transformer replacement cost in function of its nominal apparent power
- Civil engineering costs in a rural area in function of the length of the trench
- Civil engineering costs in an urban area in function of the length of the trench

As the Romande Energie and Groupe-e data is confidential, the following nomenclature of parameters will be used in the equations presented in this report:

- Romande Energie: capital letter C followed by an id letter and re (example: Ca_{re_cu}, Cb_{re_cu})
- Groupe-e: capital letter C followed by an id letter and ge (example Ca_{ge_cu}, Cb_{ge_cu})

The details of the development of the fitted cost functions are given in Appendix A.

3.2 Ancillary services exported to higher network levels

Table 3 shows the service groups considered for ancillary services export to higher network level according to deliverable D1.1. In the following sections, the data gathered for the estimation of this value will be presented.

Service Group	**Benefits for interconnected system**	**Relative value evaluation**	**Local benefits or conflicts**	**Relative value evaluation**
Frequency control	New reserve providers	*aFRR and mFRR historical value* *→ § 3.2.1*	Component loadings will be influenced	-
Voltage control	Support voltage plan	*Only relevant for NL1: tariffs according to Swissgrid voltage management* [3][3]. *→ § 3.2.2*	Voltages will be influenced	-

Table 3: Benefits and relative value determination for export services from D1.1

3.2.1 Calculation method for historical mFRR-based value

Based on the approach used in [8], the historical data of the mFRR is used in order to define the price for the flexible energy used for frequency control. Table 4 lists the maximal and mean prices for the year 2019. These values will be used in order to determine a value for services exported as well as for energy balancing in the local LV network, as indicated in Table 1 and Table 4.

[3] In this project this will not be considered: a voltage plan would be needed for the transmission grid. Alternatively, the nominal voltage could be used. This would however require to have a network model for the upstream network, including the load flows, which is not realistic for this study. A simplified average tariff method will be applied.

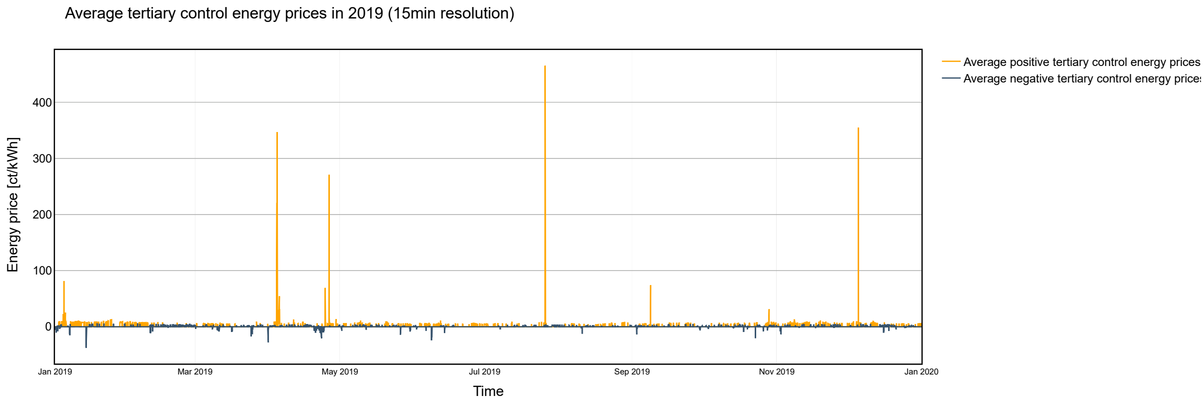

Figure 7 Tertiary control energy prices in 2019 with 15min resolution

	mFRR historical price [ct/kWh]		
	Min	Mean	Max
Positive	1.90	8.32	465.49
Negative	-37.69	0.83	5.35

Table 4 Historical price for mFRR

These results are influenced by some exceptional events occurring during the year for a little portion of the year. In order to discard these exceptional events, 0.5% of the largest values are cut off for positive energy prices and 0.5% of the smallest values for negative energy prices. The resulting graph is shown in Figure 8. Table 9 contains the data to be used within the next steps of the project.

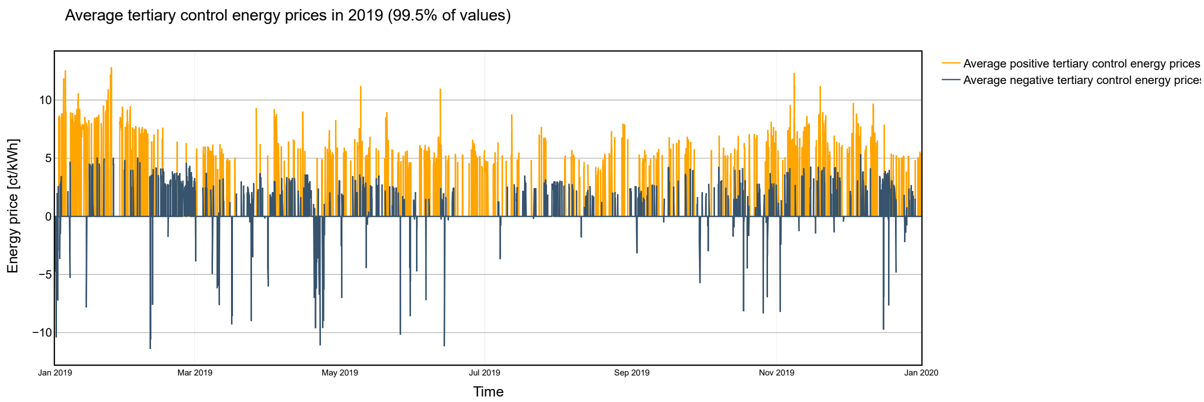

Figure 8 Average tertiary control energy prices in 2019 with 0.5% of the values cut off

	mFRR historical price [ct/kWh]		
	Min	Mean	Max
Positive	1.90	6.43	12.82
Negative	-11.40	1.36	5.35

Figure 9 Historical price of mFRR with 99.5% of the data

3.2.2 Calculation method for historical reactive power exchange-based value

Figure 10 shows the remuneration method for voltage plan adequacy of active distribution network operators in Switzerland. The remuneration is based on the exchange of reactive power with the transmission network in dependence of the voltage in the transmission network. Reactive power that contributes to maintain the voltage within its planned band is remunerated while a penalty is due when the reactive power exchange causes an increase of the voltage deviation. The rates for exchanged kVAr in for each of these cases are published by Swissgrid [9]. For the use in the DiGriFlex project, an average rate representing each situation will be used, based on previous work [8]: the remuneration that can be potentially passed on to the distributed generator is the difference between the penalty for non-conform behaviour and the remuneration for conform behaviour for 20% of the time, the 80% of the remaining time correspond to only conform behaviour. A 20% margin for the DSO (the only possible aggregator in this case) is also integrated into the calculation.

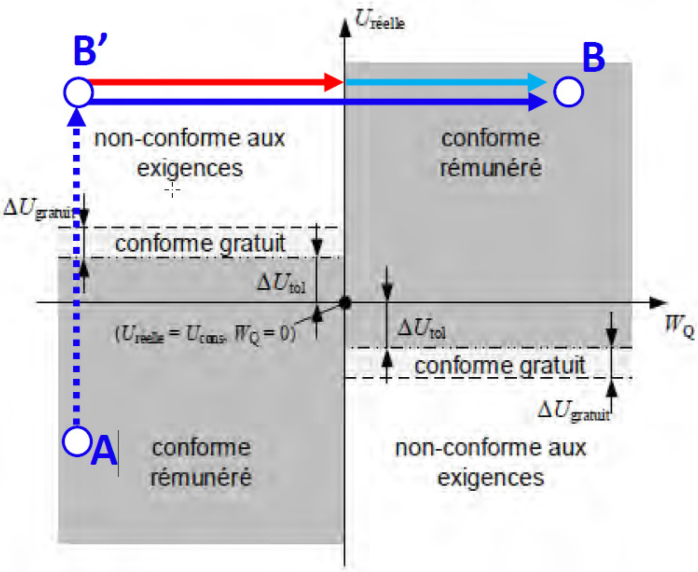

Figure 10 Example of reactive energy remuneration [3]

$$tar_{VS} = (0.2 \cdot tar_{NCZ} + 0.8 \cdot tar_{CZ}) \cdot 0.8 = 0.259 \frac{ct}{kVArh} \qquad (7)$$

The 2019 rates are used within this project, according to [9] in order to be coherent with the historical data used for other services:

- tar_{NCZ} = 0.42 ct/kVArh
- tar_{CZ} = 0.30 ct/kVArh

For reference, in 2021, the rates will be:

- tar_{NCZ} = 1.38 ct/kVArh
- tar_{CZ} = 0.30 ct/kVArh
- tar_{VS} = 0.413 ct/kVArh

4 Simulation method for network reinforcement-based value calculation

4.1 Grid areas considered

4.1.1 Rural grid area: Lucens

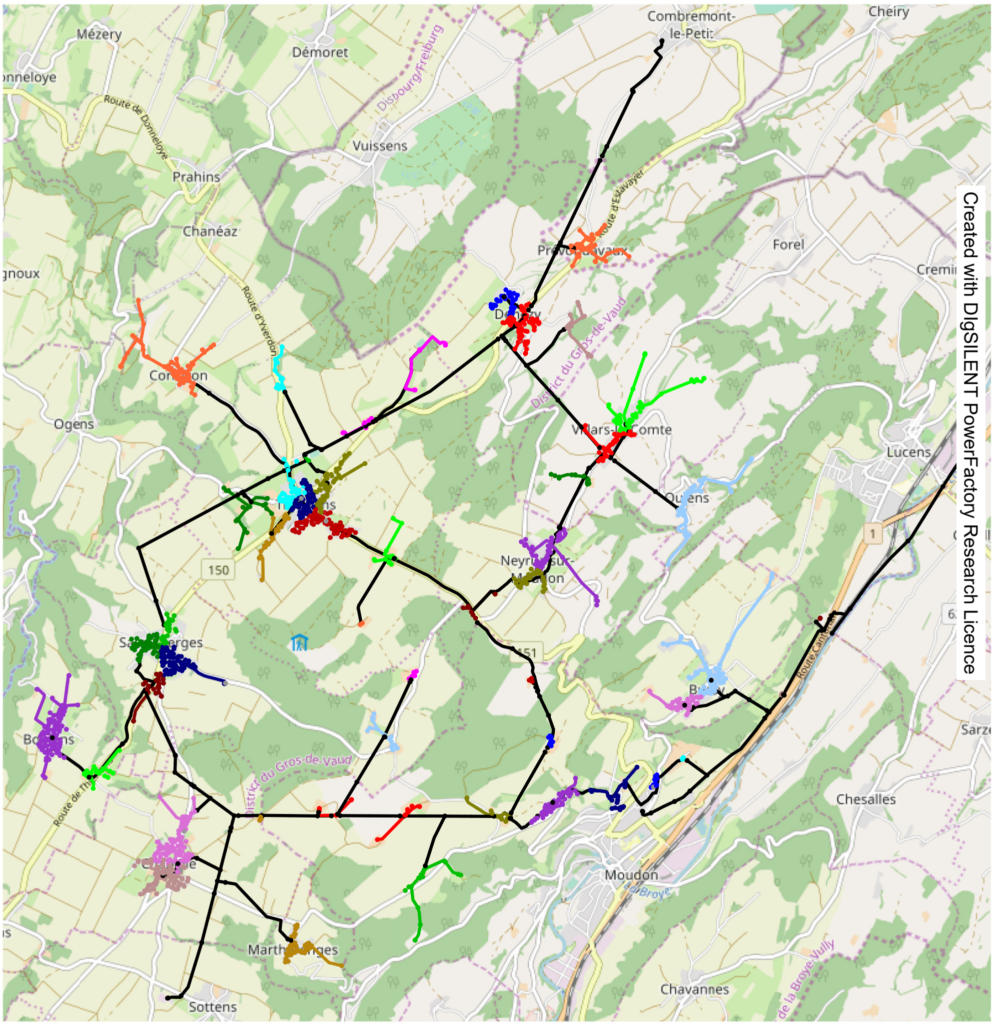

Figure 11 Geographical diagram of the Lucens network (black: MV, colours: LV)

Figure 11 represents the considered rural network, which is one of the MV feeders of the Lucens HV/MV substation of Romande Energie. The topology and component data have been extracted from Romande Energie's GIS database via its power flow calculation tool. Due to the nature and history of these tools and databases, some adjustments were required in order to obtain a functional model that was subsequently used for the hosting capacity calculations described in the next chapter. MV and LV networks are modelled up to the final customer or producer, in most cases LV consumers/producers. The rural MV feeder (including all connected LV grids) used in WP1 comprises:

- 52 LV networks

- 2164 LV loads
- 144 LV-connected PV generators

Annual loading measurement data in 15 minutes intervals is available at the HV/MV substation feeder in Lucens. Load and generation data has been estimated by creating infeed profiles based on archived meteorological data and generic load profiles for each LV load. The estimated data was scaled in order to correspond to the measured data in a student's diploma thesis [10], [11].

4.1.2 Urban grid area: Rolle

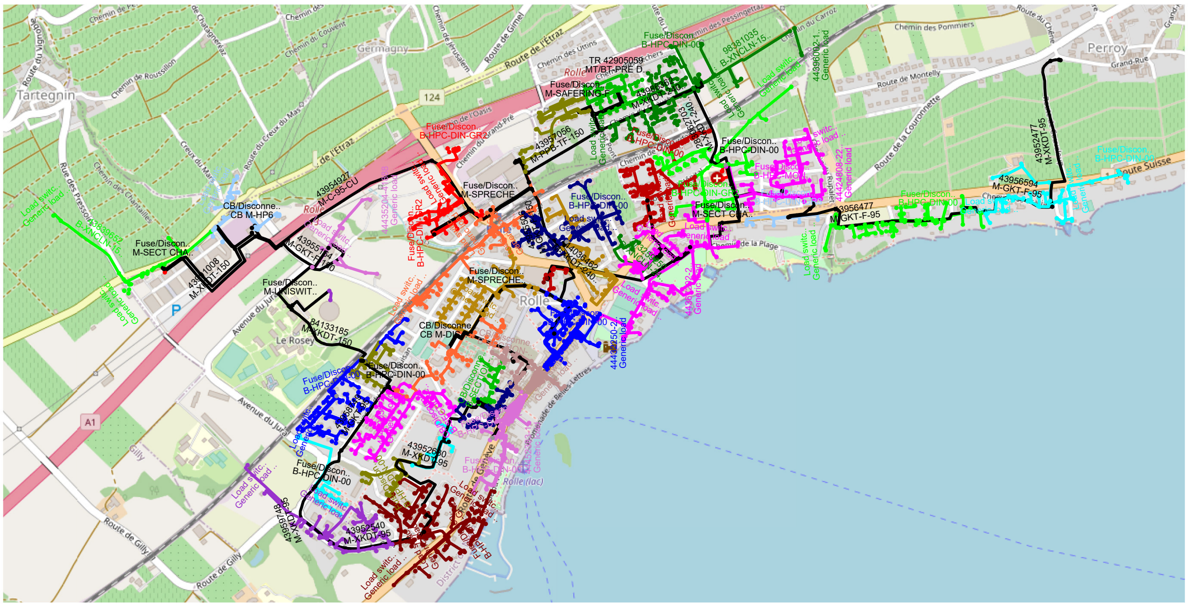

Figure 12 Geographical diagram of the Rolle network

Figure 12 shows the urban grid area considered in WP1. It consists of several MV feeders of the Rolle HV/MV substation, all serving the city of Rolle. The sources and handling of topological, component and load data are identical to the case of the rural network described in the previous section.

The grid area represented in Figure 12 comprises:

- 40 LV networks
- 4385 LV Loads
- 68 LV-connected PV generators
- 1 LV synchronous generator

4.2 Procedure for determining the relative value of flexibility based on network reinforcements

This section describes the steps required to determine the average value of flexible energy relative to the equivalent network reinforcement. This procedure has been carried out for each of the considered grid areas (urban and rural) and thus two sets of relative values have been obtained. Several choices have been made, e.g. for weighting the influence of different factors, etc. During the development and testing of the simulation procedure, several options have been considered. This report focuses on the final choices, but the models and scripts have of course been developed with the possibility to flexibly change the parameters.

$\mathbf{E_1}$ = annual energy before grid reinforcement

$\mathbf{E_2}$ = annual energy after grid reinforcement

$\mathbf{N_{LV}}$ = list of low voltage networks

$\mathbf{n_{host\text{-}nodes}}$ = number of host nodes in the considered network

$\mathbf{H_{nodes}}$ = list of host nodes in the considered network

$\mathbf{P_{lim1}}$ = hosting power for reinforcement calculation

$\mathbf{P_{lim2}}$ = hosting power after reinforcement calculation

$\boldsymbol{\alpha_{max}}$ = maximum division factor for the calculated limit power

$\boldsymbol{\alpha_{min}}$ = minimum division factor for the calculated limit power

$\boldsymbol{\alpha_{LV}}$ = calculated division factor for the considered network

$\boldsymbol{\beta}$ = step between maximum and minimum division factor for the considered $n_{host\text{-}nodes}$

$\mathbf{P_{lim1\text{-}tot}}$ = sum of all the hosting powers calculated for the network

$\mathbf{P_{All\text{-}tot}}$ = total power to allocate at the new hosts/loads

4.2.1 Step 1: initial hosting capacity

Figure 13 shows the details of the first step, which is to identify the hosting capacity of the grid in its initial state, before any reinforcement or need to use flexibility. The hosting capacity represents the upper limit of the amount of load or generation that can be added to the considered network before action (reinforcement or use of flexibility) is needed. The limits are defined by combining the ampacity constraints of the grid components and the voltage limits in the LV network. The DiGriFlex project idea becomes relevant to any energy exceeding this initial hosting capacity.

As shown in Figure 13, the hosting capacity is determined within an LV network taken individually, the calculation being repeated until each LV network has been investigated. In each LV network, the hosting capacity is calculated for 4 distant nodes and one node close to the distribution transformer, again individually. Figure 14 shows an example for the selection of these nodes. The result is the hypothetical capacity that could be added at one (and only one) of the investigated nodes.

As a last step, a load / generation increase scenario is created by combining load / generation increases at the previously investigated nodes. In order to obtain realistic increases of the total load / generation for a single reinforcement step, a division factor is used to reduce the load / generation added collectively compared to the individually computed hosting capacity. The distribution of the additional load / generation on the investigated nodes is random. Load and generation are investigated separately in order to obtain two limits, one for added generation, and the other for added load.

This step thus finishes with a load / generation scenario requiring a network reinforcement or active network management.

Figure 15 shows an additional check which is required for the creation of the additional load / generation scenario: in case the LV networks have a topology that does not allow for five nodes to be investigated in terms of hosting capacity, a lower number of host nodes is used. As a consequence, the steps shown in the figure are followed in order to adapt the division factors and the random repartition of the additional load / generation. This is done to ensure that the network effectively needs reinforcement after addition of the load / generation.

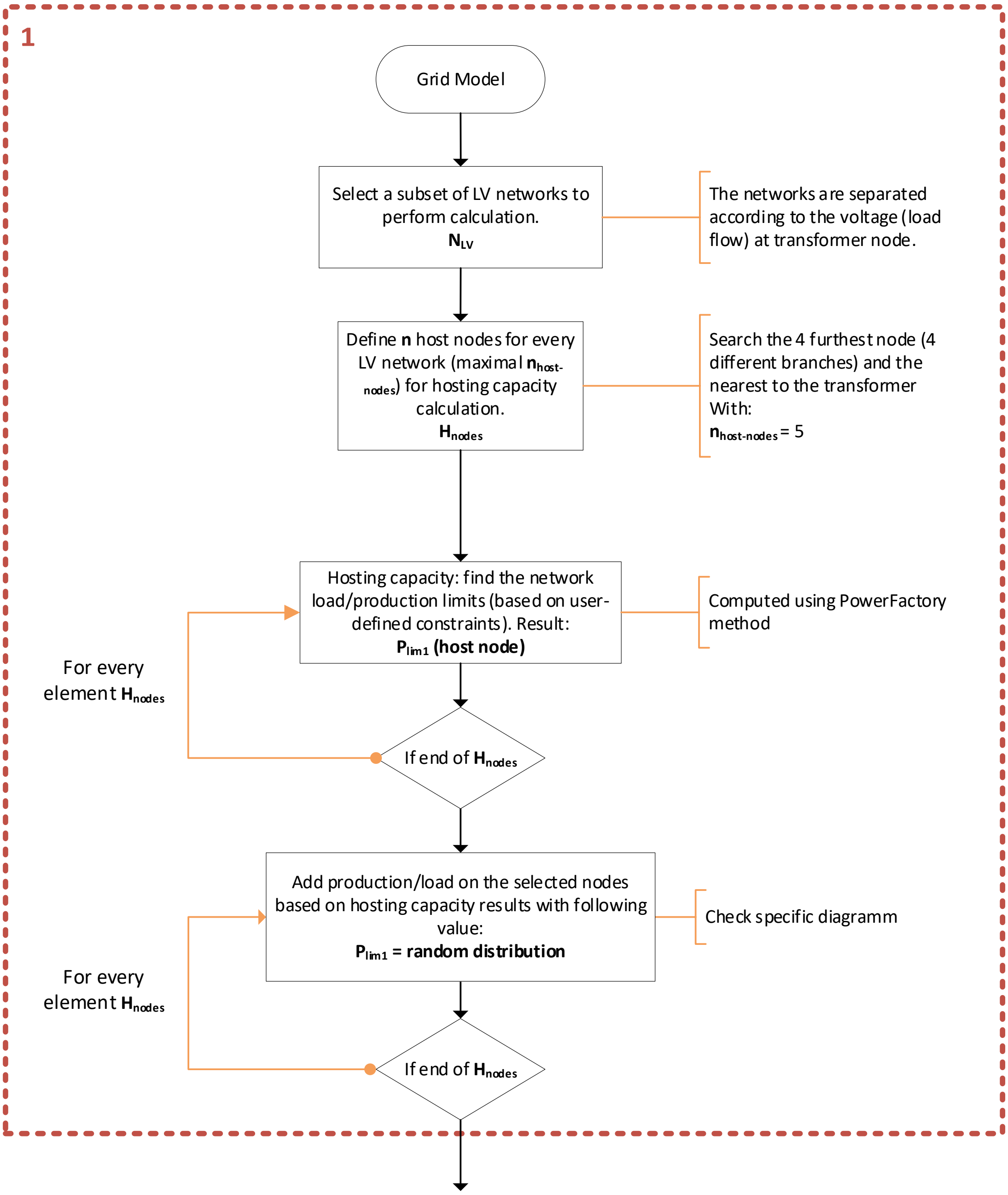

Figure 13 Step 1 for grid reinforcement calculation: hosting capacity calculation

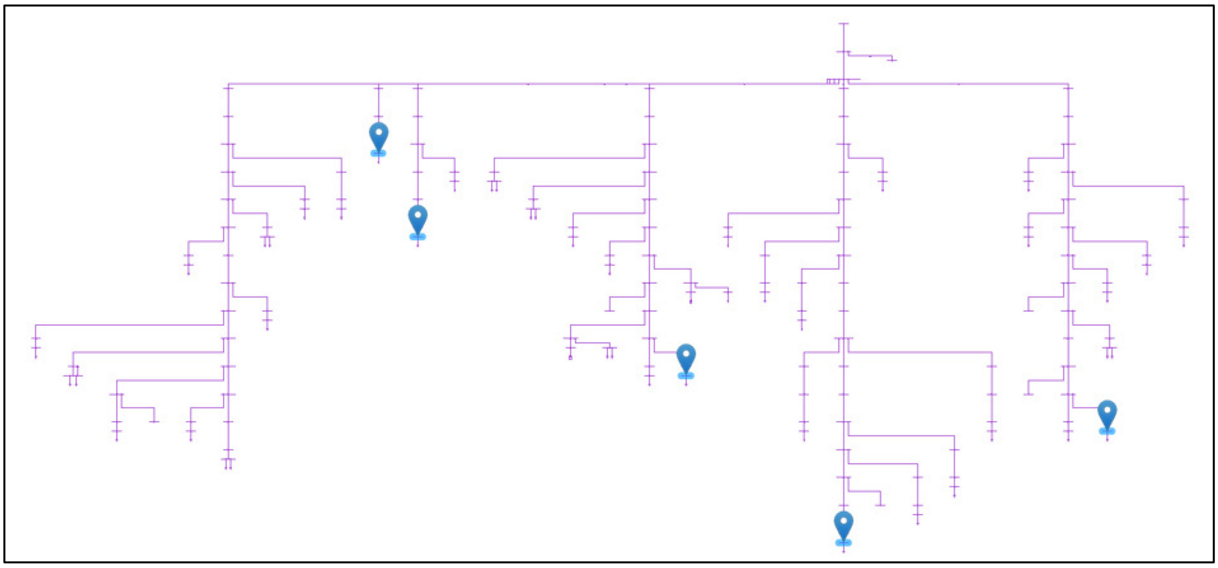

Figure 14 Example of host nodes in Chermet LV network

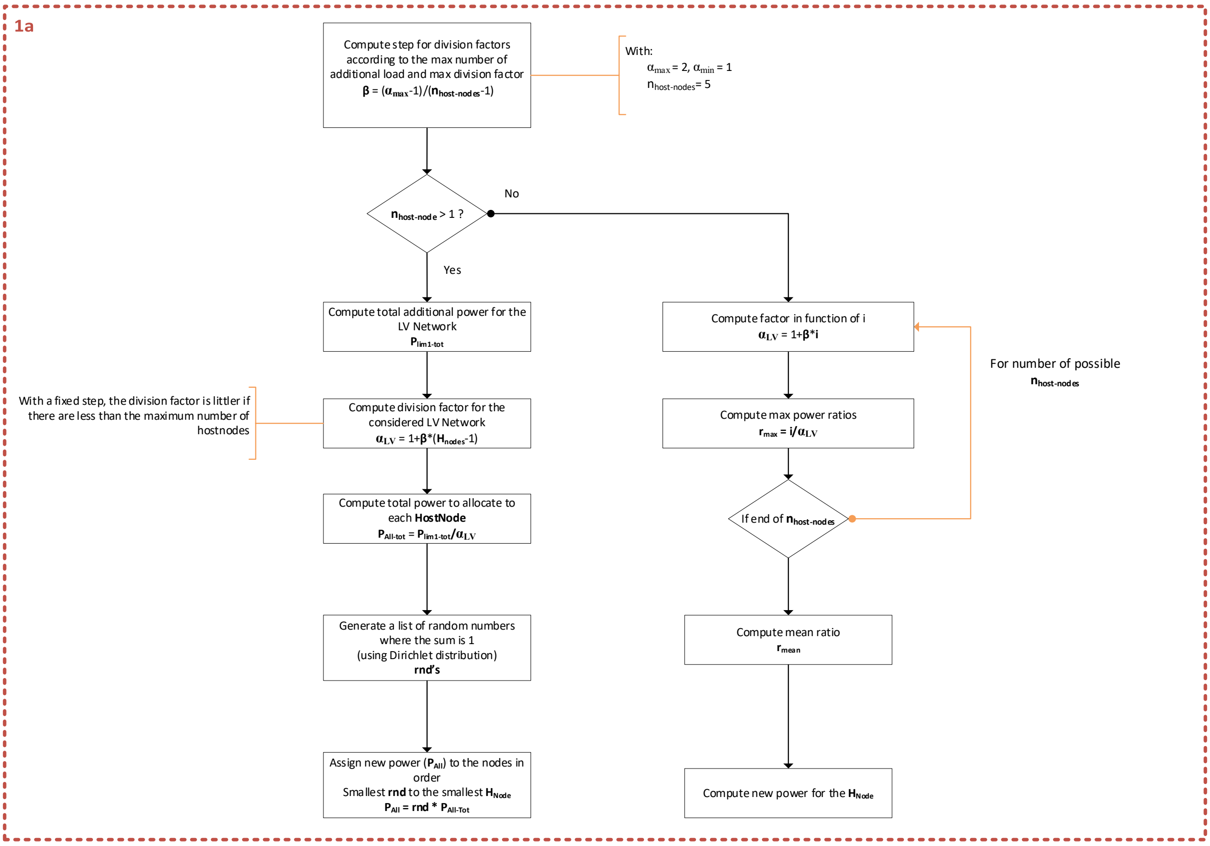

Figure 15 Definition of the random distribution, verification

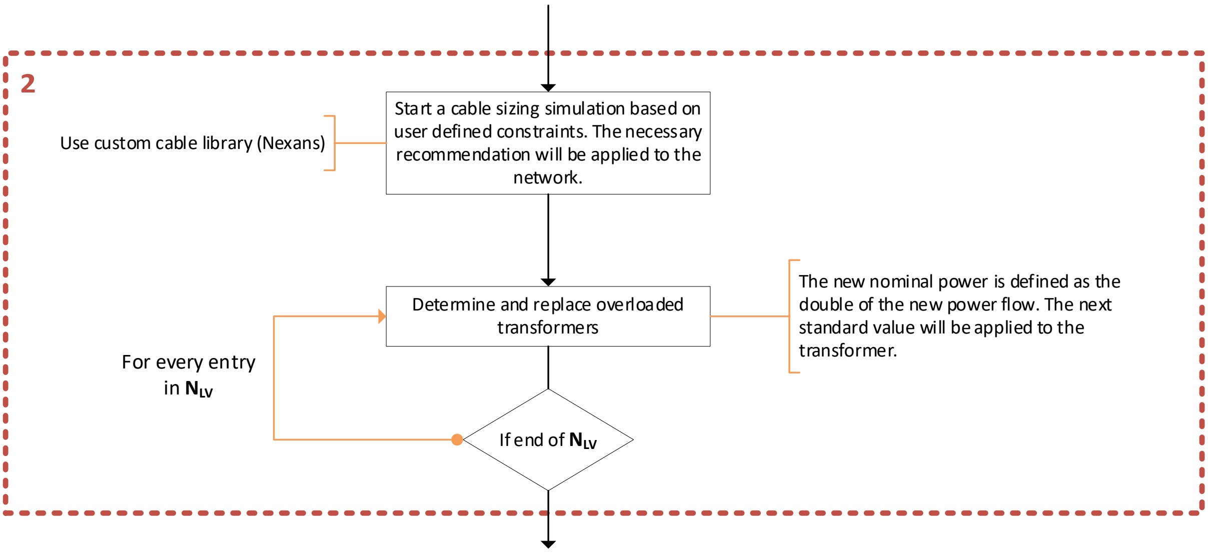

Figure 16 Step 2 for grid reinforcement calculation (cables and transformers sizing)

4.2.2 Step 2: determining the required network reinforcement

In this step, shown in Figure 16, the additional load / generation scenario from Step 1 is used in order to determine which network components need to be replaced as a network reinforcement measure. This is done for every LV network separately.

The components used for the reinforcement are standard cable types (adapted from [12]) and transformers. For each cross-section and apparent power, only one component type is considered, i.e. there is no other decision made, e.g. with respect to the efficiency of transformers or similar.

The result is a reinforced network, where only the components are upgraded for lager cable / line cross-sections and transformers are upgraded to a higher apparent power if needed.

4.2.3 Step 3: determining the hosting capacity of the reinforced network

The third step is the determination of the hosting capacity for the reinforced grid. A process (Figure 17) similar to the evaluation of the hosting capacity before reinforcement is applied, based on five host nodes. Since reinforcement is done in relatively large increments, the hosting capacity is higher than the load / generation increase in the scenario considered. For further evaluation in the project, this potential further use of the capacity in the reinforced network is taken into account.

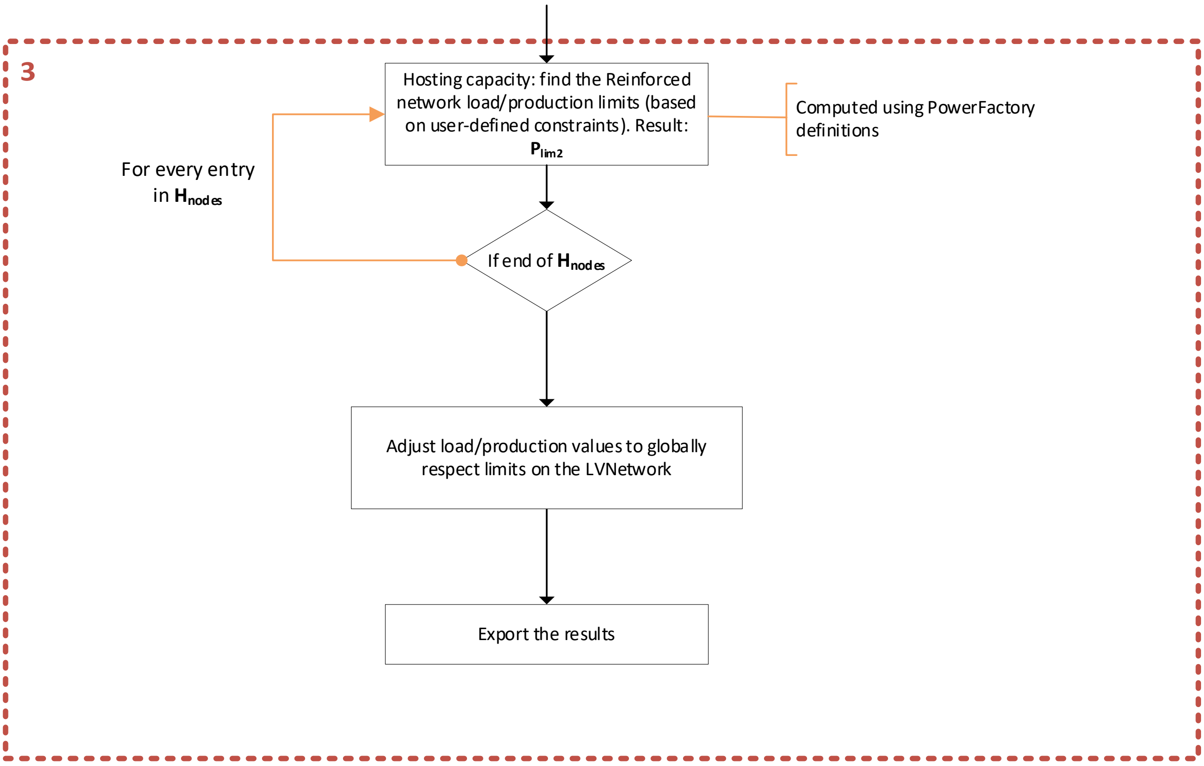

Figure 17 Step 3 for grid reinforcement simulation (find new LOAD/DER limits)

4.2.4 Step 4: determining the additional energy flow permitted by the reinforcement

Figure 18 shows how an annual power flow calculation is set up and performed. The required network reinforcements (for added generation and added load) are integrated into the network model. New load and generation profiles are added for the network participants included in the generation / load increase determined in the preceding step. On this basis, a quasi-dynamic simulation (QDS) is performed before and after the reinforcement. This allows a comparison of the energy injected or drawn from the network in both situations.

The outcome of this final step is the additional annual energy flowing after the reinforcement and the amount of energy flowing when the initial capacity of the network is exceeded (see Figure 5 and Figure 6).

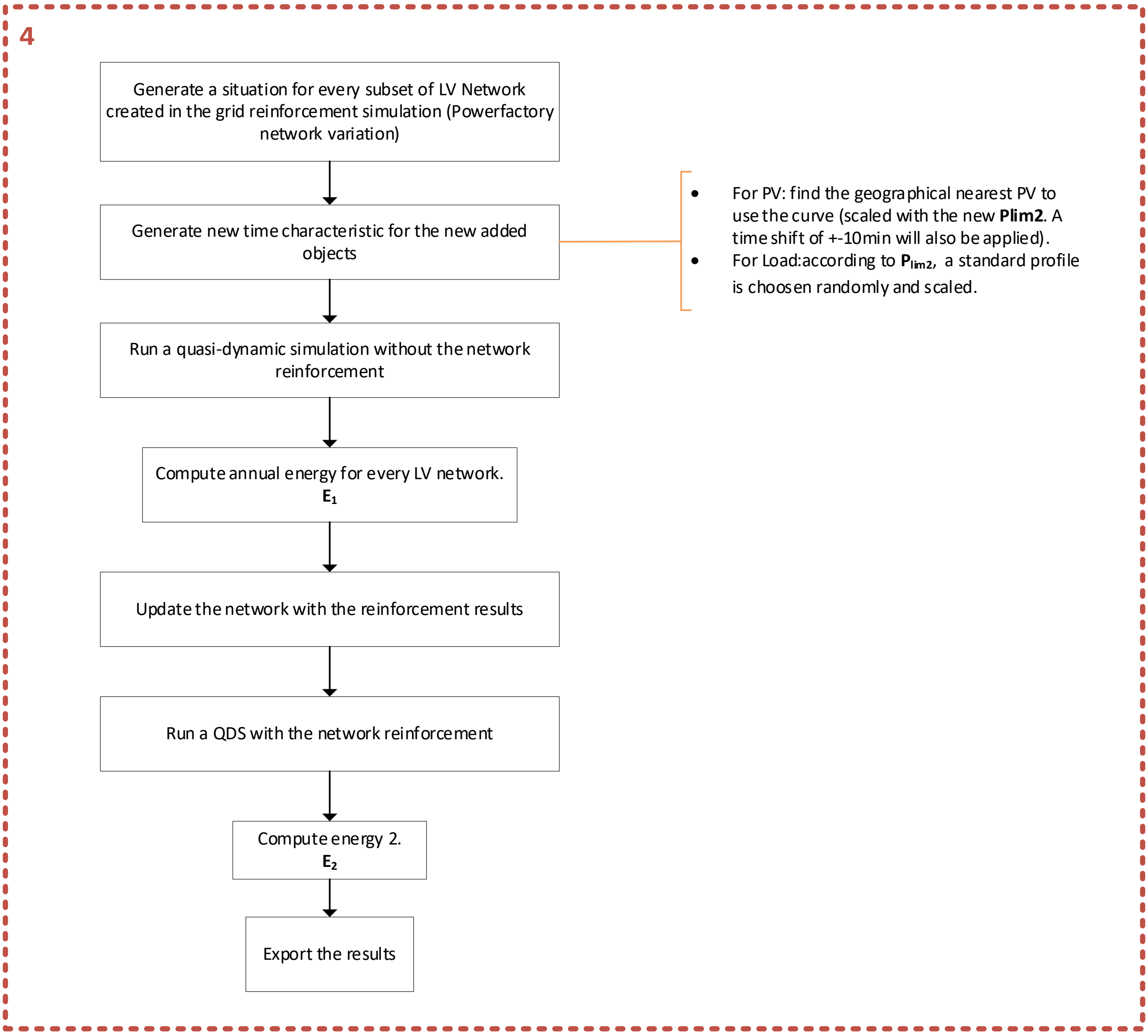

Figure 18 Step 4 for relative value calculation (quasi dynamic simulations)

4.3 Results

This section summarises the results for each network (rural and urban) and distinguished between the effect of additional load and additional generation.

4.3.1 Rural network results with additional DER

First, the results for the addition of generation into the rural grid area of Lucens are introduced. This will allow to determine the value of flexible generation reduction or load increase. The following parameters (referring to chapter 4.2 and 3.1.1) have been chosen for the simulation of the rural network and its reinforcement:

- $\alpha_{Max} = 2$
- r = 3.83 %
- n = 40 years

In Figure 19, the hosting capacity of each LV network is shown before (blue) and after (orange) network reinforcement. This data is the result of simulation steps 1 to 3 discussed in the previous section. The stations are ordered by hosting capacity. The results reveal the following underlying assumptions: first it is assumed that where the distribution transformer has a high power before the reinforcement, the odds are better to see an addition of load or generation, thus the added generation / load is dependent on the initial network "size". Second, this added capacity is also linked to the initial hosting capacity, indicating that where a capacity currently exists, the reason could be (but obviously does not have to be) that the capacity will be needed in the near future. The authors consider (after some discussions with the DSOs) that these assumptions are sensible.

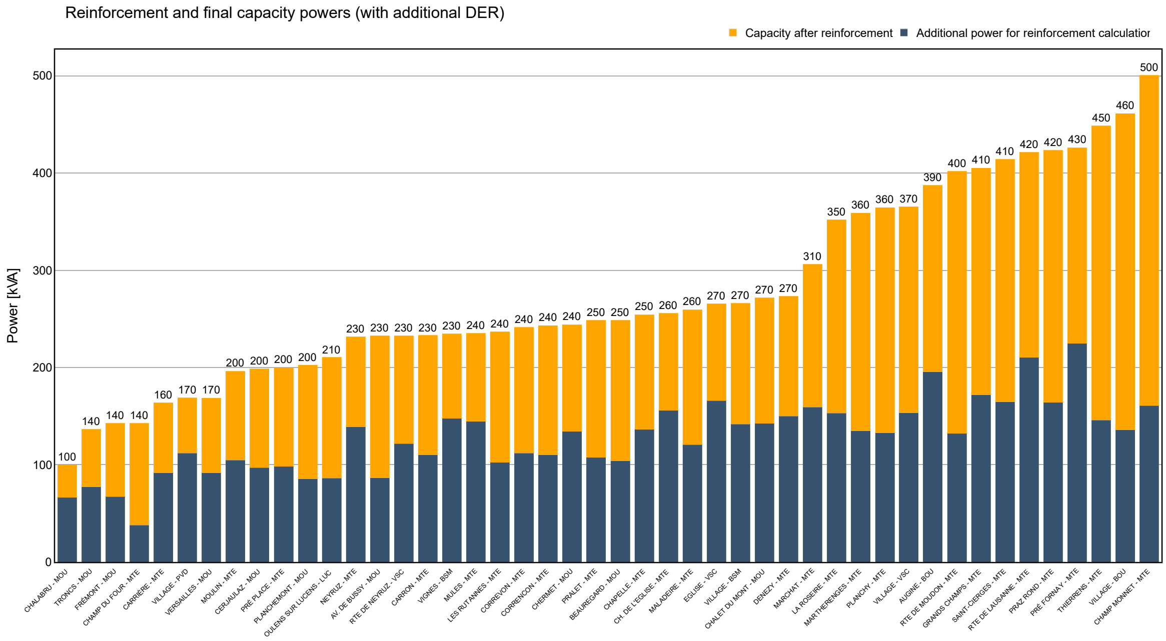

Figure 19 Total hosting capacity (for additional generation) before (blue) and after (orange) network reinforcement of LV networks in Lucens

Figure 20 shows the peak power flow (corresponding to the peak generation situation, which is relevant for components sizing in this case) in the distribution transformer for each LV network for three different load / generation scenarios:

- Initial state of the networks (blue)
- With the additional power (generation) scenario used for the reinforcement calculation (orange)
- With the maximal additional power after the reinforcement calculation, i.e. full use of the hosting capacity after reinforcement (green)

The negative power flows in Figure 20 represent a generation excess that is reinjected into the MV network.
The total reinforcement costs are presented in Figure 21 for each LV network. A high variance of the costs per network can be observed. This shows that either the value of flexibility must be assessed for each specific case, or, when considering future and generic scenarios, the assessment must be based on averages obtained by studying a substantial number of cases. The latter approach is applied in the DigriFlex project.

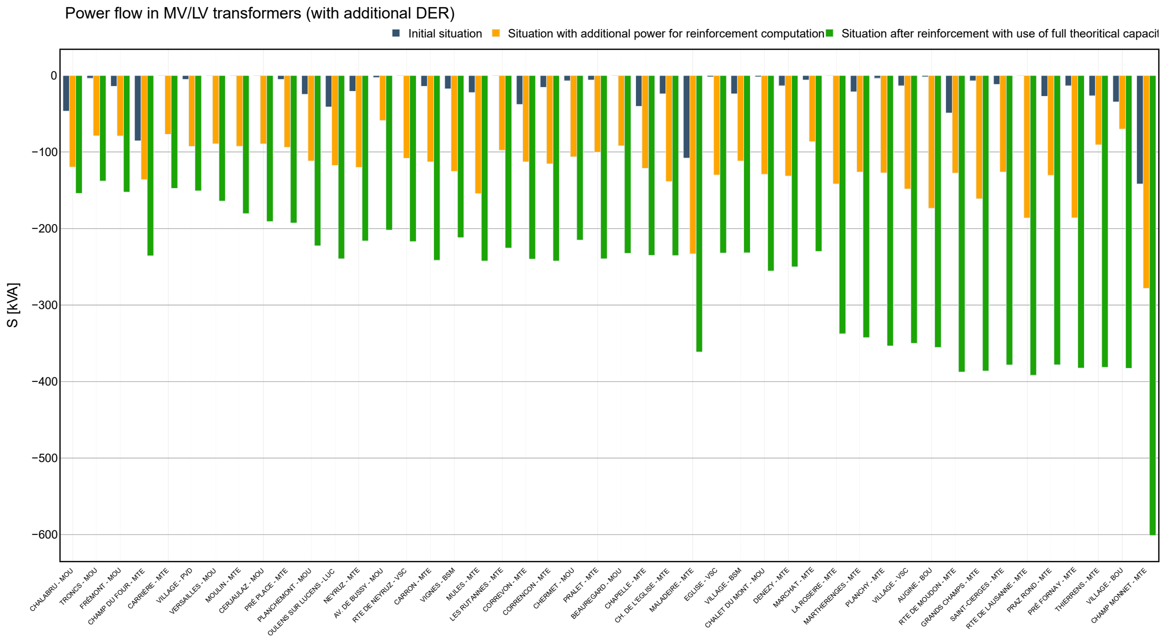

Figure 20 Power flow in every LV network at initial state (blue), with additional production for reinforcement calculation (orange) and with reinforced network and maximal additional generation (green)

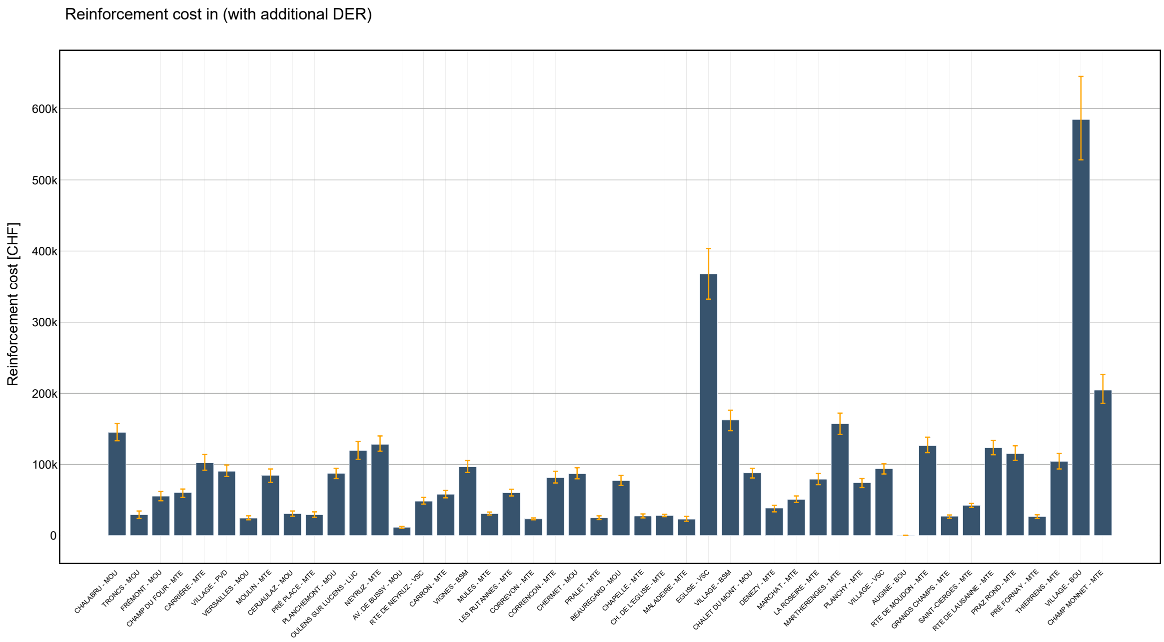

Figure 21 Reinforcement cost for every LV network in Lucens in case of additional generation

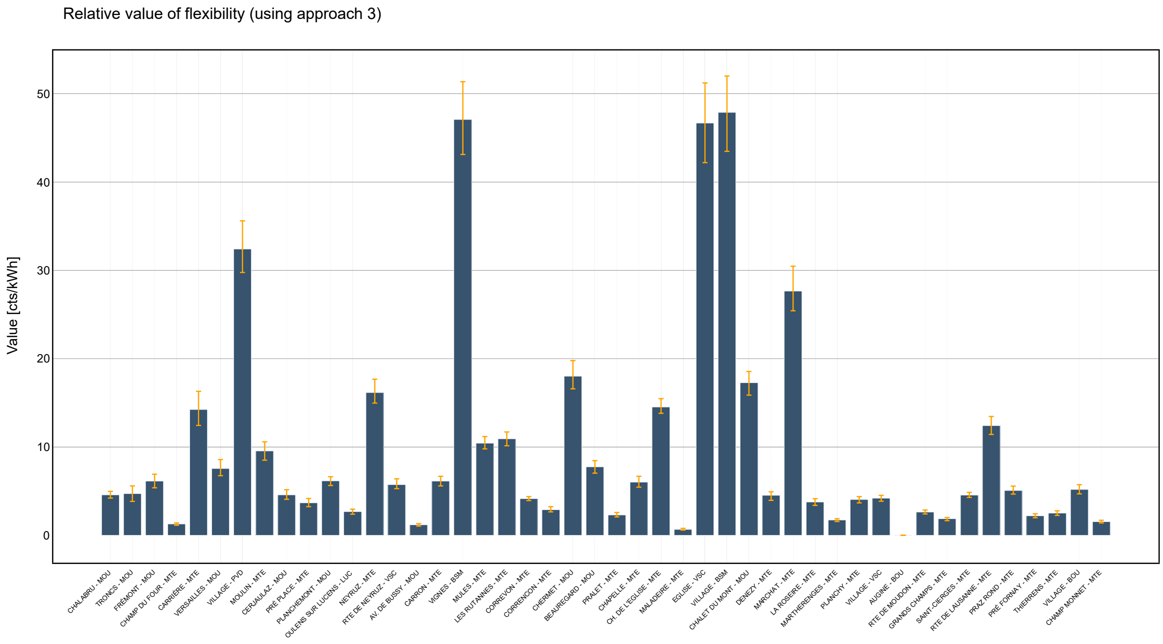

Figure 22 Relative value of flexibility for each LV network in Lucens (using calculation approach 3 according to chapter 3.1.1) in case of additional generation

Finally, the relative value of flexibility for each LV network is shown in Figure 22. This relative value is obtained as discussed in section 3.1.1, where the energy taken into account is the energy flowing through the distribution transformer in excess of the considered LV network's initial hosting capacity. For comparison, the alternative definitions for the additional energy that have been dismissed after analysis are shown in Appendix B.

For the evaluation of the relative value of the flexible energy within the entire grid area, a weighted average calculation is introduced. The results are shown in Table 5. Three weighting methods for the average are used:

- According to transformer nominal power (after reinforcement)
- According to the total additional power
- According to ΔE (see chapter 3.1.1)

The third approach is considered to be the best one to describe the effective value for the flexible energy. For this reason, only these values will be used for the following calculations. The weighted average according to the portion of energy over capacity level is the most interesting metric since it weighs the flexibility according to the actual use of the additional hosting capacity induced by its use.

		Min	**Mean**	**Max**
Weighted average according to MV/LV transformer nominal power	ct/kWh	7.57	8.30	9.8
Weighted average according to capacity after reinforcement	ct/kWh	8.16	8.94	9.78
Weighted average according to the portion of energy over capacity level	ct/kWh	4.40	4.82	5.27

Table 5 Weighted averages of relative value of flexible energy in Lucens in case of additional generation

4.3.2 Rural network results with additional load (Lucens)

This section introduces the results for a similar analysis in the rural grid area, this time for additional load. This will allow to determine the value of flexible load reduction or generation increase.

The same parameters (referring to chapter 4.2 and 3.1.1) have been chosen as for the case of generation increase:

- $\alpha_{Max} = 2$
- $r = 3.83$ %
- $n = 40$ years

In Figure 23 the hosting capacity of each LV network is shown before (blue) and after (orange) network reinforcement.

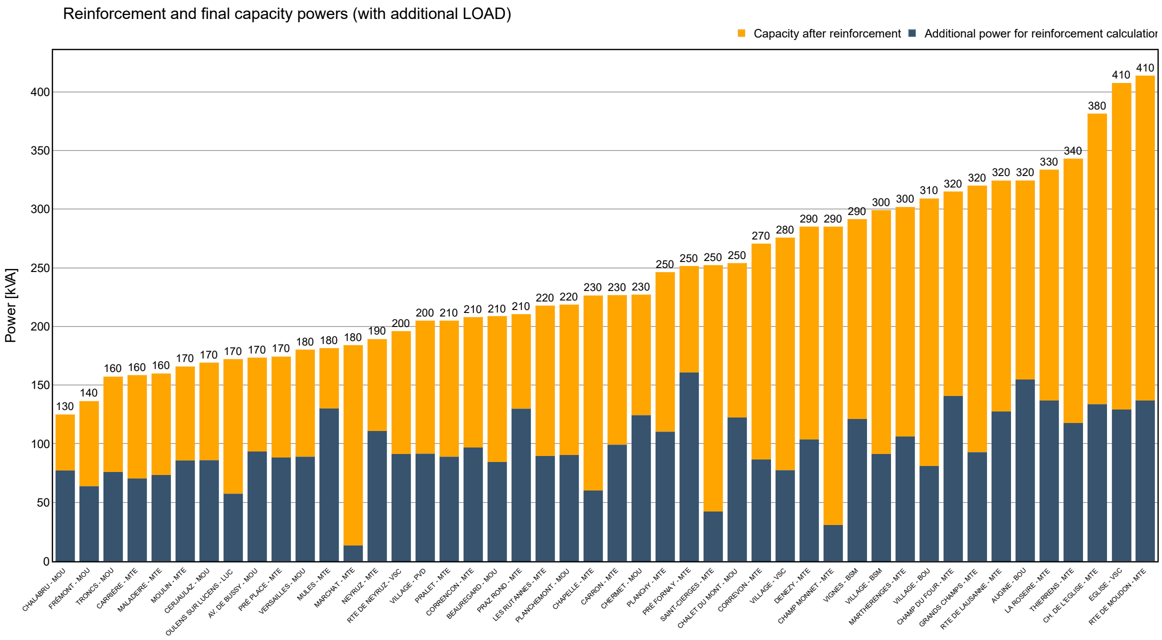

Figure 23 Total hosting capacity (for additional consumption) before (blue) and after (orange) network reinforcement of LV networks in Lucens

Figure 24 shows the peak power flow (corresponding to the peak load situation, which is relevant for components sizing in this case) in the distribution transformer for each LV network for three different load / generation scenarios:

- Initial state of the networks (blue)
- With the additional power (load) scenario used for the reinforcement calculation (orange)
- With the maximal additional power after the reinforcement calculation, i.e. full use of the hosting capacity after reinforcement (green)

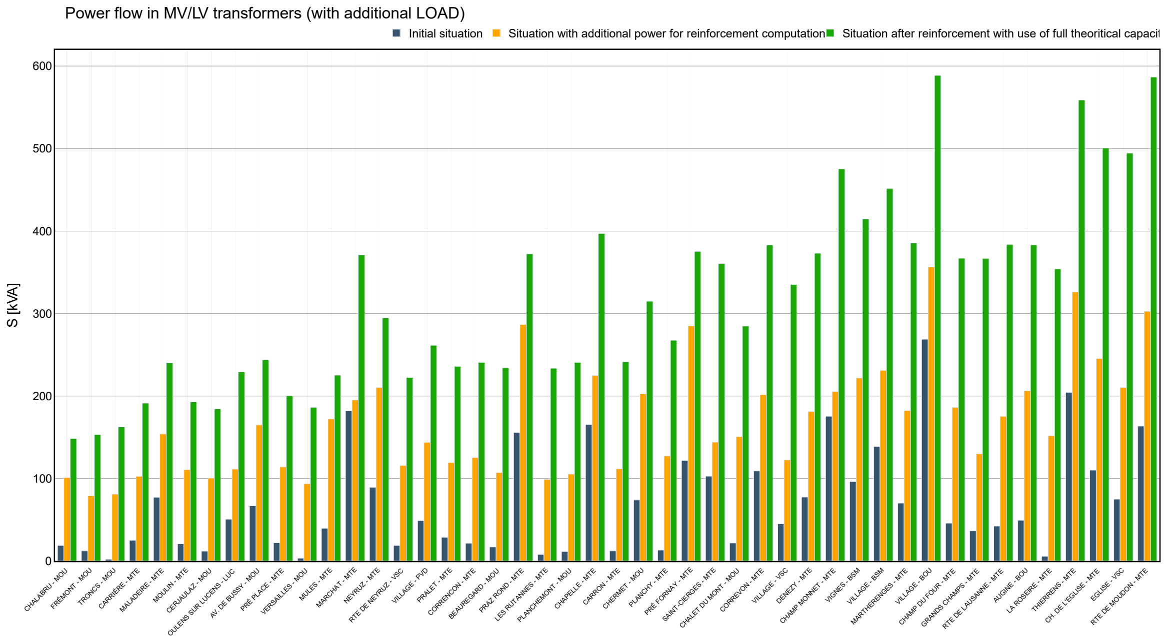

Figure 24 Power flow in every LV network at initial state (blue), with additional production for reinforcement calculation (orange) and with reinforced network and maximal additional consumption (green)

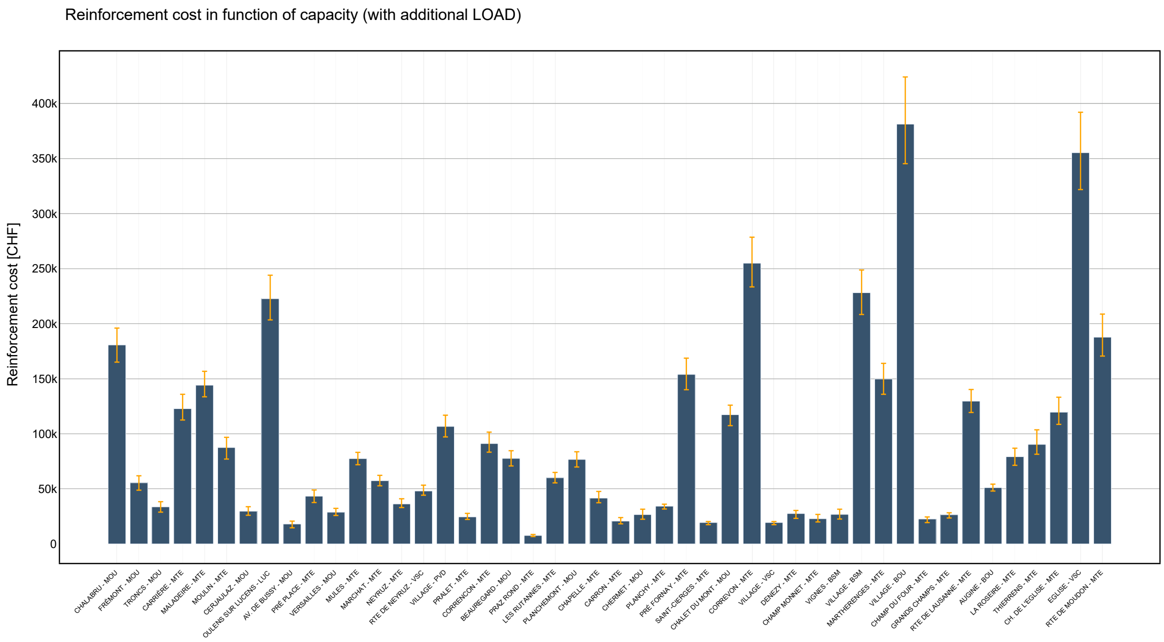

Figure 25 Reinforcement cost for every LV network in Lucens in case of additional consumption

The total reinforcement costs are presented in Figure 25 for each LV network.

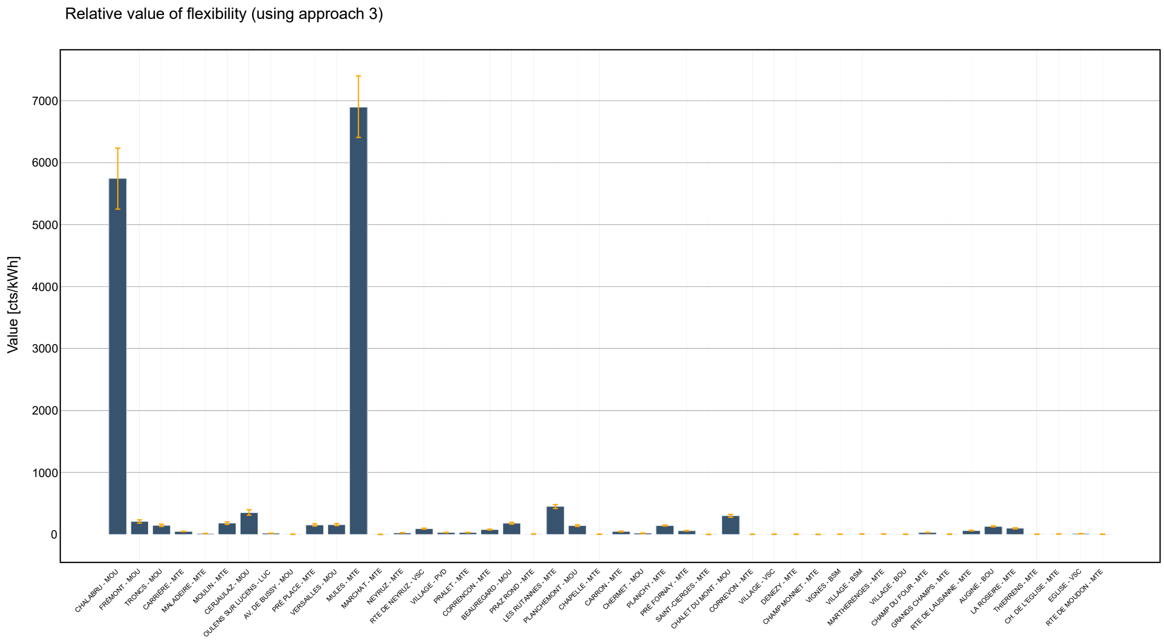

Figure 26 Relative value of flexibility for each LV network in Lucens (using calculation approach 3 according to chapter 3.1.1) in case of additional consumption

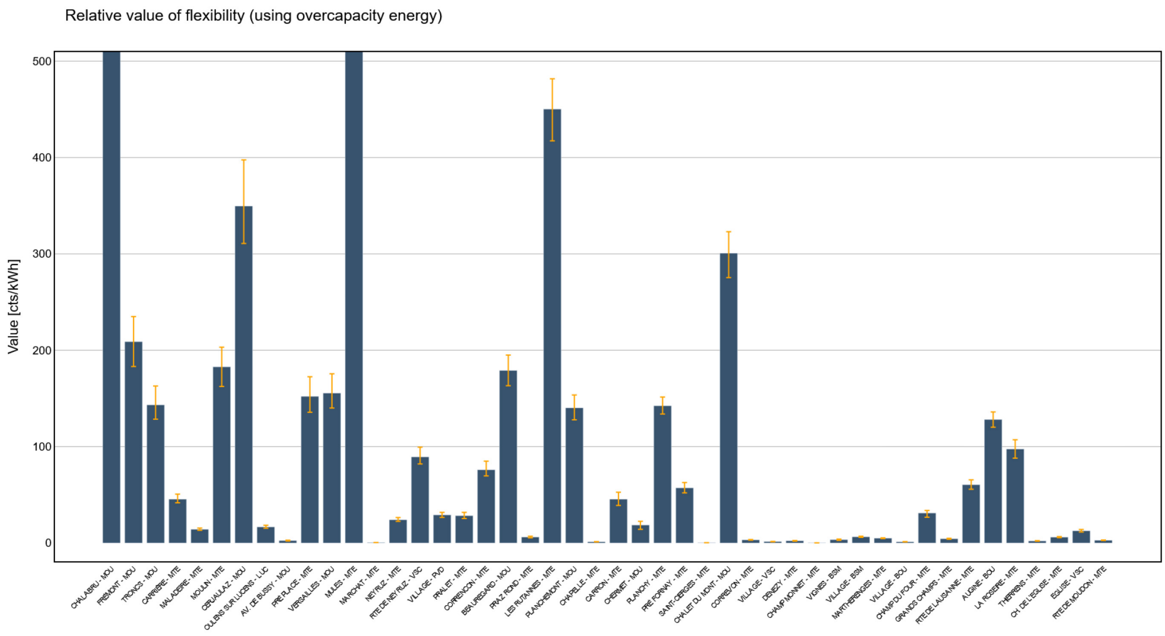

Figure 27 Relative value of flexibility for each LV network in Lucens (using calculation approach 3 according to chapter 3.1.1) in case of additional consumption (zoom)

Finally, the relative value of flexibility for each LV network is shown in Figure 26 and their average value is summarised in Table 6. This case illustrates the issue of averaging the automatically performed network reinforcement-based values. In Figure 26, two cases are really unattractive in terms of investment, since the investment is made for a very small amount of additional energy. A further explanation for this is the high amount of DG already present in the initial network: the need for flexible load reduction is very unlikely in this case. In practice such an investment would have been dismissed, a fact that is not included in the evaluation of the simulations presented here. Instead, the weighted averaging used here leads to the same effect of reducing (nearly eliminating) the effect of such unrealistic cases.

		Min	**Mean**	**Max**
Weighted average according to MV/LV transformer nominal power	ct/kWh	176.99	192.48	208.51
Weighted average according to capacity after reinforcement	ct/kWh	218.84	237.96	257.70
Weighted average according to the portion of energy over capacity level	ct/kWh	3.74	4.12	4.54

Table 6 Weighted averages of relative value of flexible energy in Lucens in case of additional consumption

According to the choices discussed in chapter 4.3.2, the weighted average according to the portion of energy over capacity level will be considered as the final result.

4.3.3 Urban network with additional generation (Rolle)

The parameters (referring to chapter 4.2 and 3.1.1) chosen as for this case are slightly different, reflecting the fact that the urban network tends to be stronger (due to the lower distances and higher shares of cables):

- α_{Max} = 1.75
- r = 3.83 %
- n = 40 years

In Figure 28, the additional possible power before (blue) and after (orange) reinforcement of the respective LV network is shown.

Figure 29 shows the peak power flow in the distribution transformer for each LV network for three different load / generation scenarios. For the considered urban networks, the highest load initially was a load situation, whereas after addition of generation, the most constraining case became a generation (export) case. The cases shown are:

- Initial state of the networks (blue): in most cases, the relevant maximal flow corresponds to a load situation.
- With the additional power (load) scenario used for the reinforcement calculation (orange).
- With the maximal additional power after the reinforcement calculation, i.e. full use of the hosting capacity after reinforcement (green).

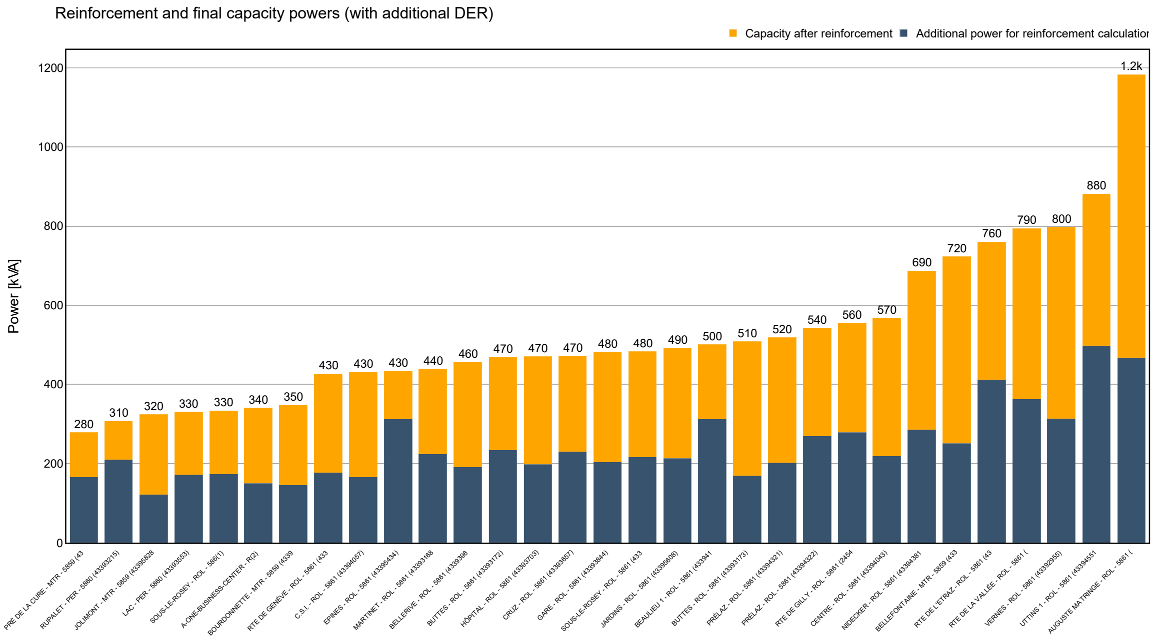

Figure 28 Total hosting capacity (for additional generation) before (blue) and after (orange) network reinforcement of LV networks in Rolle

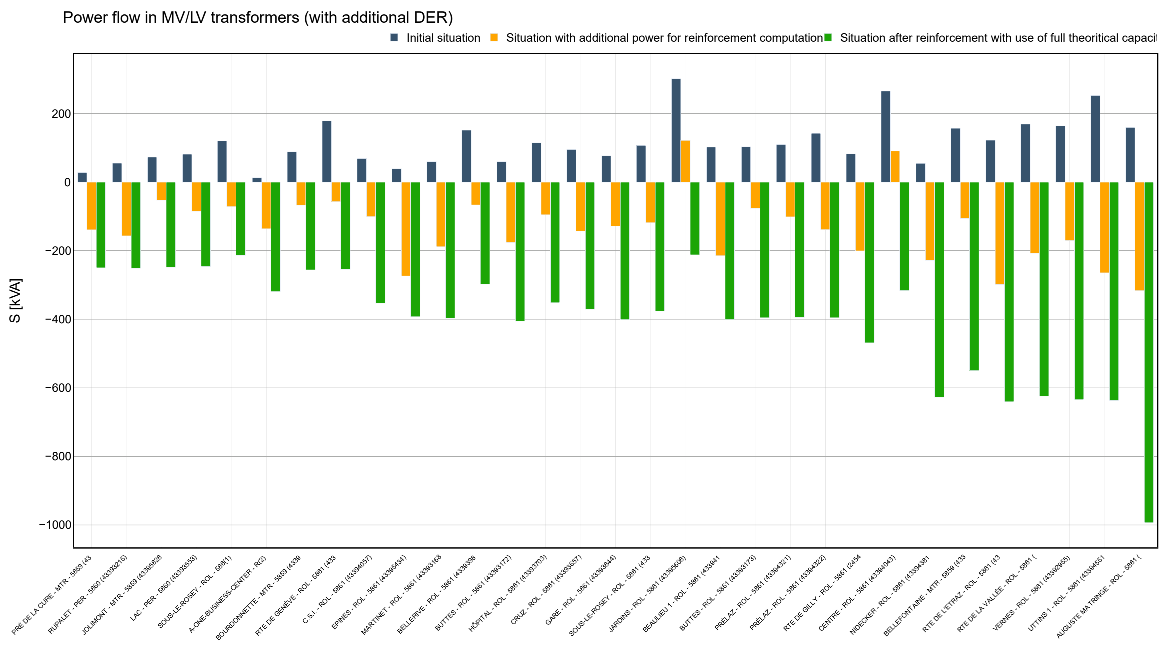

Figure 29 Power flow in every LV network at initial state (blue), with additional production for reinforcement calculation (orange) and with reinforced network and maximal additional production (green)

The total reinforcement costs are presented in Figure 30 for each LV network and the value per unit of flexible energy is shown in Figure 31. In comparison with the rural networks, the costs appear to be lower. Two factors contribute to this effect: first, distances are smaller within the urban environment, hence line reinforcements tend to be less expensive despite the higher cost of civil engineering per length. Second, the networks in the considered area tends to have higher reserve margins (especially on cable links) than the considered rural network. For the relative value that is relatively high, the explanation is the same as previously: this is a case where a high investment leads to almost no additional energy transit, and hence needs to be discarded from a practical perspective.

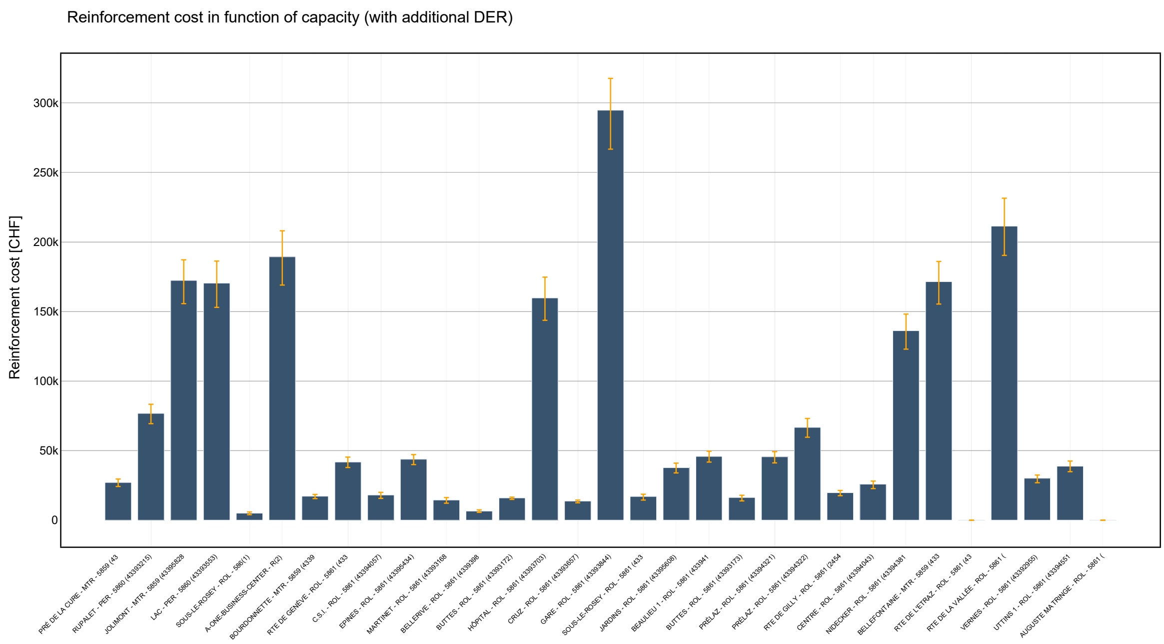

Figure 30 Reinforcement cost for every LV network in Rolle in case of additional generation

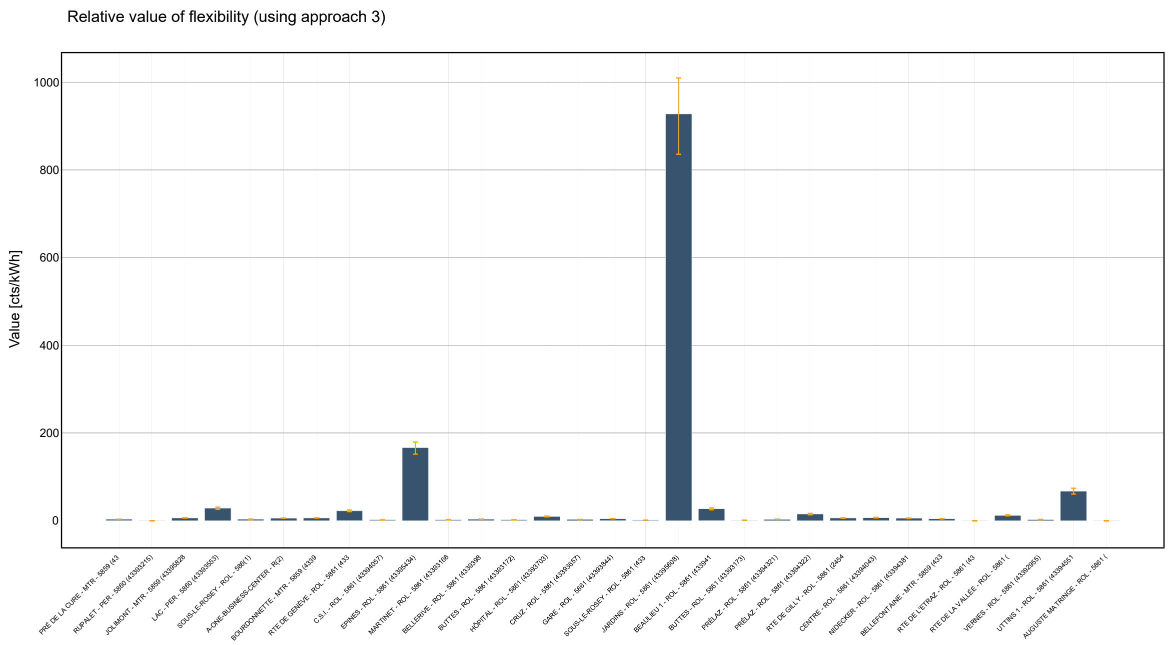

Figure 31 Relative value of flexibility for each LV network in Rolle (using calculation approach 3 according to chapter 3.1.1) in case of additional generation

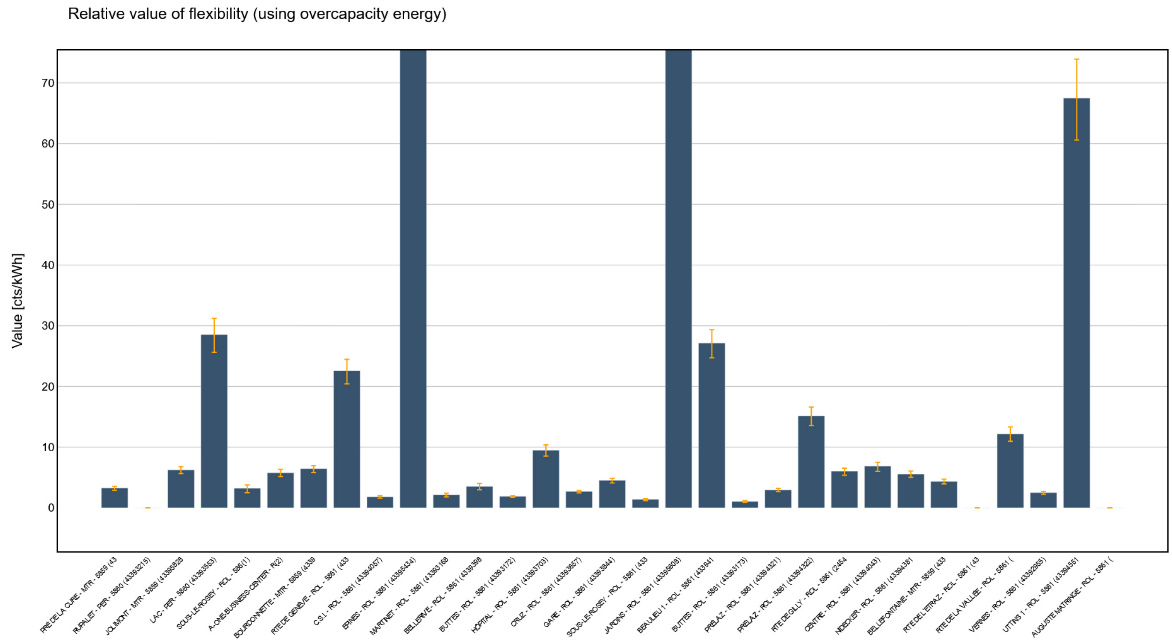

Figure 32 Relative value of flexibility for each LV network in Rolle (using calculation approach 3 according to chapter 3.1.1) in case of additional generation (zoom)

The weighted average of the flexibility value in this case is summarised in Table 7. Again, the meaningful value is the third option, i.e. weighting by the amount of additional energy transiting in the distribution transformer.

		Min	Mean	Max
Weighted average according to MV/LV transformer nominal power	ct/kWh	45.29	50.26	54.70
Weighted average according to capacity after reinforcement	ct/kWh	37.44	41.54	45.20
Weighted average according to the portion of energy over capacity level	ct/kWh	5.48	6.11	6.66

Table 7 Weighted averages of relative value of flexible energy in Rolle in case of additional generation

4.3.4 Urban network with additional load (Rolle)

The simulation parameters (referring to chapter 4.2 and 3.1.1) are the same as for the case of added generation:

- α_{Max} = 1.75
- r = 3.83 %
- n = 40 years

In Figure 33 the hosting capacity of each LV network is shown before (blue) and after (orange) network reinforcement.

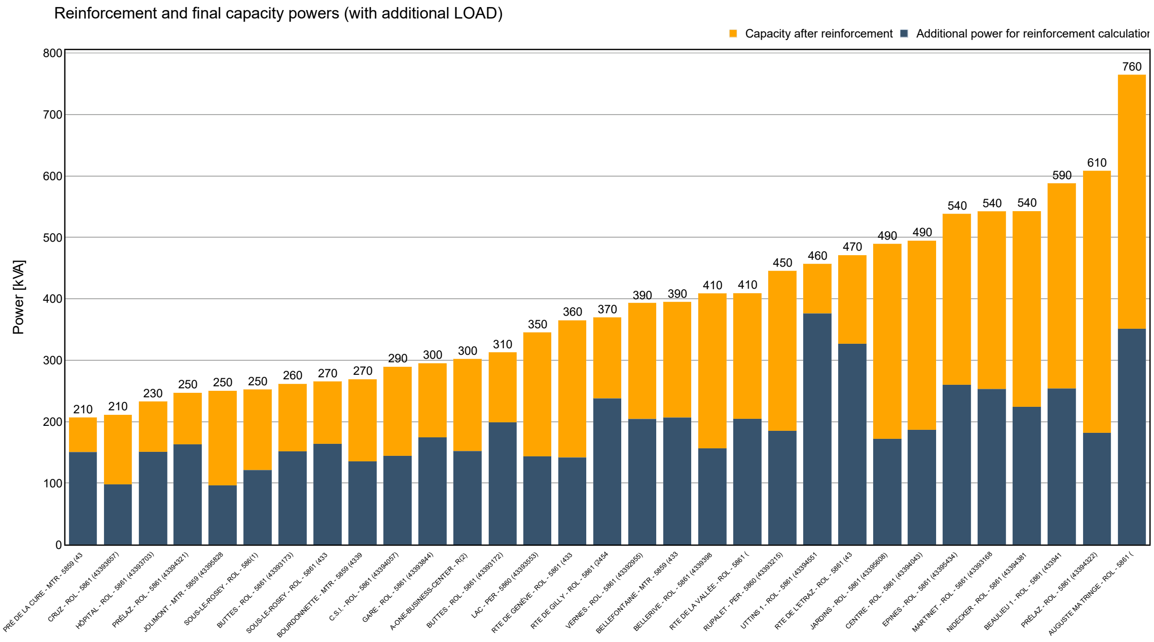

Figure 33 Total hosting capacity (for additional consumption) before (blue) and after (orange) network reinforcement of LV networks in Rolle

Figure 34 shows the peak power flow in MV/LV transformers and Figure 35 shows the reinforcement cost associated with the addition of load to the urban grid area.

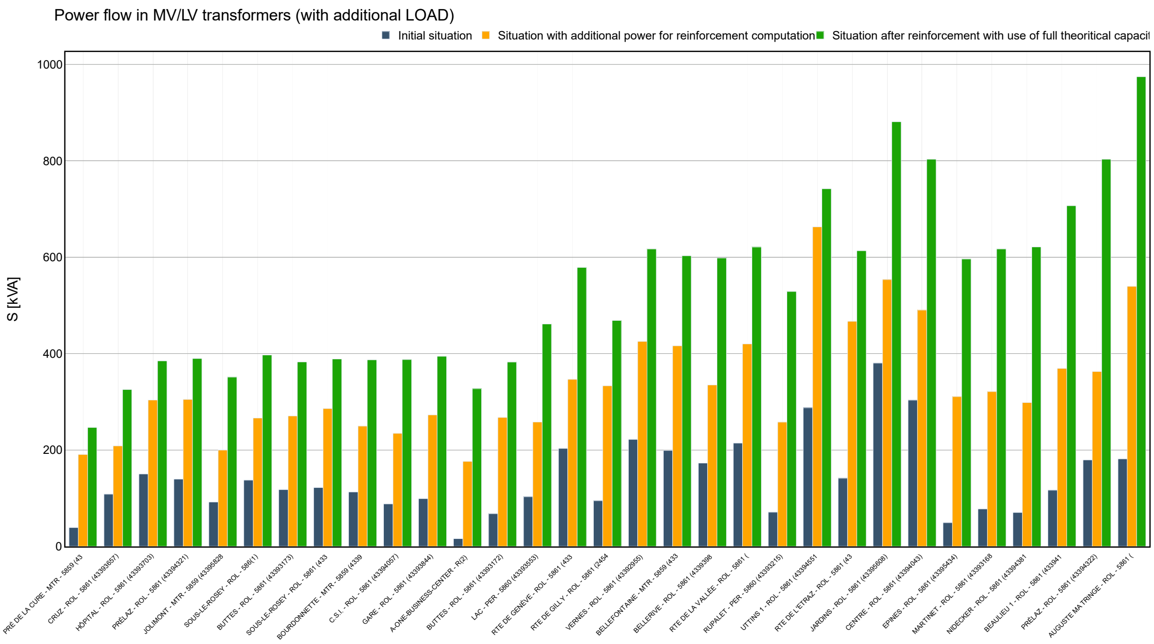

Figure 34 Power flow in every LV network at initial state (blue), with additional consumption for reinforcement calculation (orange) and with reinforced network and maximal additional consumption (green)

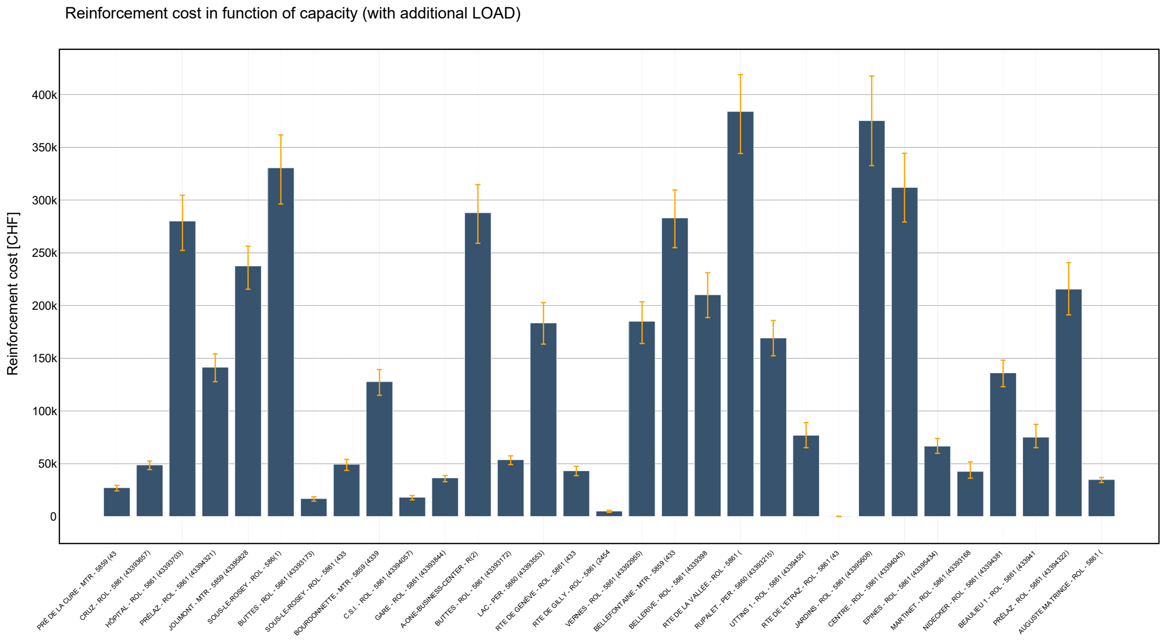

Figure 35 Reinforcement cost for every LV network in Rolle in case of additional consumption

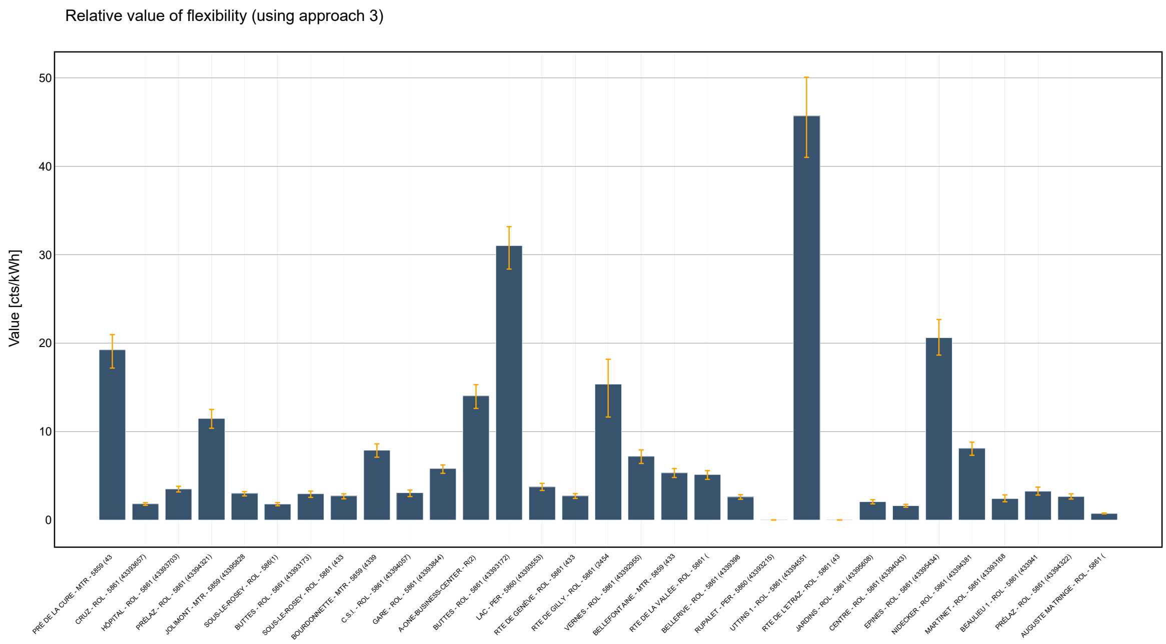

Figure 36 Relative value of flexibility for each LV network in Rolle (using calculation approach 3 according to chapter 3.1.1) in case of additional consumption

The weighted average of the flexibility value shown in Figure 36 in this case is summarised in Table 8. Again, the meaningful value is the third option, i.e. weighting by the amount of additional energy transiting in the distribution transformer.

		Min	**Mean**	**Max**
Weighted average according to MV/LV transformer nominal power	ct/kWh	7.84	8.80	9.69
Weighted average according to capacity after reinforcement	ct/kWh	6.59	7.40	8.14
Weighted average according to the portion of energy over capacity level	ct/kWh	3.20	3.58	3.95

Table 8 Weighted averages of relative value of flexible energy in Rolle in case of additional consumption

5 Results summary

The tables below summarise the results in terms of relative value for the flexibility uses identified in WP1 for further use within the Digriflex project.

5.1 Local use

Service group	Value for interconnected system			Value for local system Rural area			Value for local system Urban area		
	min	mean	max	min	mean	max	min	mean	max
Balancing in ct/kWh	-11.40	1.36	5.35	4.40	4.82	5.27	5.48	6.11	6.66
Voltage control in ct/kVArh	-	0.26	-	1.70	3.32	17.20	1.70	3.32	17.20
Congestion management in ct/kWh	-11.40	1.36	5.35	4.40	4.82	5.27	5.48	6.11	6.66

Table 9 Values for flexible generation decrease (or flexible consumption increase)

Service group	Value for interconnected system			Value for local system Rural area			Value for local system Urban area		
	min	mean	max	min	mean	max	min	mean	max
Balancing in ct/kWh	1.90	6.43	12.82	3.74	4.12	4.54	3.20	3.58	3.95
Voltage control in ct/kVArh	-	0.26	-	1.70	3.32	17.20	1.70	3.32	17.20
Congestion management in ct/kWh	1.90	6.43	12.82	3.74	4.12	4.54	3.20	3.58	3.95

Table 10 Values for flexible generation increase (or flexible consumption decrease)

5.2 Export

Service group	Value for interconnected system		
	min	mean	max
Balancing in ct/kWh	-11.40	1.36	5.35
Voltage control in ct/kVArh	-	0.26	-

Table 11 Values for flexible generation decrease (or flexible consumption increase)

Service group	Value for interconnected system		
	min	mean	max
Balancing in ct/kWh	1.90	6.43	12.82
Voltage control in ct/kVArh	-	0.26	-

Table 12 Values for flexible generation increase (or flexible consumption decrease)

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[13] The SciPy community, « scipy.optimize.curve_fit — SciPy v1.5.2 Reference Guide ». https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html (consulté le août 06, 2020).
[14] The SciPy community, « scipy.optimize.least_squares — SciPy v1.5.2 Reference Guide ». https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.least_squares.html#scipy.optimize.least_squares (consulté le août 06, 2020).

A Fitted cost functions

This annex describes the development of the fitted cost functions used in the project for the calculation of investment costs. If needed, the python script "equations_anonymised.py" can be analysed, in order to understand the details of the calculations.

Definition of the symbols used:

- A: section in mm^2
- S: nominal apparent power in VA
- L: distance in m
- c: cost in CHF

CU Cables equations definition:

Groupe-e CU Cables cost equation is already defined:

$$c_{ge\_cu} = (Ca_{ge\_cu} \cdot A^2 + Cb_{ge\_cu} \cdot A + Cc_{ge\_cu}) \cdot L + Cd_{ge\_cu} \quad (8)$$

The VSE equation for CU cable cost can be fitted[4] using the provided data from VSE. The resulting function after the fitting calculation is as follows:

$$c_{vse\_cu} = (0.00005 \cdot A^2 + 0.36685 \cdot A + 18.12768) \cdot L + 1938.63056 \quad (9)$$

As only one example for one specific case is available for Romande Energie, more calculations have to be performed in order to estimate the following cost equation.

$$c_{re\_cu} = (Ca_{re\_cu} \cdot A^2 + Cb_{re\_cu} \cdot A + Cc_{re\_cu}) \cdot L + Cd_{re\_cu} \quad (10)$$

First, an equation the describes the mean between VSE and Groupe-e data is calculated:

$$\bar{c}_{ge,vse} = mean(c_{ge\_cu}, c_{vse\_cu}) \quad (11)$$

$$\bar{c}_{ge,vse} = (\overline{Ca}_{ge,vse} \cdot A^2 + \overline{Cb}_{ge,vse} \cdot A + \overline{Cc}_{ge,vse}) \cdot L + \overline{Cd}_{ge,vse} \quad (12)$$

The parameter $\overline{Ca}_{ge,vse}$ and $\overline{Cb}_{ge,vse}$ are used for Ca_{re_cu} and Cb_{re_cu} as they define the shape of the curve. c_{re_cu} and Cd_{re_cu} are extrapolated from Romande Energie base data, as they only define an offset. The Cc_{re_cu} parameter is calculated for the cable case give in the example invoice.

$$Cc_{re\_cu} = \frac{(c_{re\_cu} - Cd_{re\_cu})}{L} - Ca_{re\_cu} \cdot A^2 - Cb_{re\_cu} \cdot A \quad (13)$$

[4] Fitting is achieved using the "curve_fit" function from the "scipy" python package. Non-linear least squares are used to fit a function. Check [13], [14] for more information.

AL Cables equations definition

Groupe-e AL Cables cost equation is already defined:

$$c_{ge\_al} = (Ca_{ge\_al} \cdot A^2 + Cb_{ge\_al} \cdot s + Cc_{ge\_al}) \cdot L + Cc_{ge\_al} \quad (14)$$

The VSE equation for AL cable cost can be fitted[5] using the provided data from VSE. The resulting function after the fitting calculation is as follows:

$$c_{vse\_al} = (-0.00002 \cdot A^2 + 0.11067 \cdot A + 25.53026) \cdot L + 3971.34101 \quad (15)$$

As no example is available for Romande Energie, more calculations have to be performed in order to estimate the cost equation. The main idea is to compute the medium ratio between AL and CU cables costs of Groupe-e and use this as a factor multiplication for c_{re_cu}, in order to calculate c_{re_al}

First, the mean relative cost proportion between AL and CU cable (using Groupe-e data) is computed for different combination of sections and distances

A = 95, 150 and 240 mm2

L = 100, 200, 500 and 1000 m

$$c_{ratio} = \frac{(Ca_{ge\_al} \cdot A^2 + Cb_{ge\_al} \cdot A + Cc_{ge\_al}) \cdot L + Cd_{ge\_al}}{(Ca_{ge\_cu} \cdot A^2 + Cb_{ge\_cu} \cdot A + Cc_{ge\_cu}) \cdot L + Cd_{ge\_cu}} \quad (16)$$

For every section, a mean value for all distances is calculated.

$$\bar{c}_{ratio} = mean(c_{ratio}) \quad (17)$$

Using this data, a ratio equation in function of the section can be fitted.

$$\bar{c}_{ratio}(A) = Ca_{ratio} \cdot A + Cb_{ratio} \quad (18)$$

Thanks to this equation, now the cost for aluminium cables can be calculated:

$$c_{re\_al} = c_{re\_cu} \cdot \bar{c}_{ratio}(A) \quad (19)$$

Using the above formula, an equation for the AL cost for Romande Energie can be fitted.

$$c_{re\_al} = (Ca_{re\_al} \cdot A^2 + Cb_{re\_al} \cdot A + Cc_{re\_al}) \cdot L + Cd_{re\_al} \quad (20)$$

[5] Fitting is achieved using the "curve_fit" function from the "scipy" python package. Non-linear least squares are used to fit a function. Check [13], [14] for more information.

Transformer cost equations

Using the provided data, it is possible to find the three transformer equations by fitting the knowns points.

$$c_{ge\_tr} = Ca_{ge\_tr} \cdot S^2 + Cb_{ge\_tr} \cdot S + Cc_{ge\_tr} \tag{21}$$

$$c_{vse\_tr} = -0.00760 \cdot S^2 + 35.96138 \cdot S + 7133.6153 \tag{22}$$

$$c_{re\_tr} = Ca_{re\_tr} \cdot S^2 + Cb_{re\_tr} \cdot S + Cc_{re\_tr} \tag{23}$$

Civil engineering costs equations

There are two types of civil engineering costs, depending on the topology of the network: rural and urban.

For rural areas, the equations are already defined using the standard data.

$$c_{ge\_ex\_ru} = Ca_{ge\_ex\_ru} \cdot L + Cb_{ge\_ex\_ru} \tag{24}$$

$$c_{vse\_ex\_ru} = 80 \cdot L \tag{25}$$

$$c_{re\_ex\_ru} = Ca_{re\_ex\_ru} \cdot L + Cb_{re\_ex\_ru} \tag{26}$$

For urban areas, the Romande Energie data is not given. The ratio between civil engineering costs in rural and urban environments will thus be assumed to be identical for Romande Energie and Groupe-e.

$$c_{ge\_ex\_ur} = Ca_{ge\_ex\_ur} \cdot L + Cb_{ge\_ex\_ur} \tag{27}$$

$$c_{vse\_ex\_ur} = 330 \cdot L \tag{28}$$

$$c_{re\_ex\_ur} = \frac{Ca_{re\_ex\_ru}}{Ca_{ge\_ex\_ru}} \cdot Ca_{ge\_ex\_ur} + Cb_{re\_ex\_ur} = Ca_{re\_ex\_ur} + Cb_{re\_ex\_ur} \tag{29}$$

B Relative value of flexibility for alternative definitions of the additional energy after network reinforcement

Figure 38 show the results for relative values of flexible energy using approach 1 for every LV network in Lucens (described in chapter 3.1.1). The energy difference between the annual load flow simulation before and after network reinforcement is used here for the calculations.

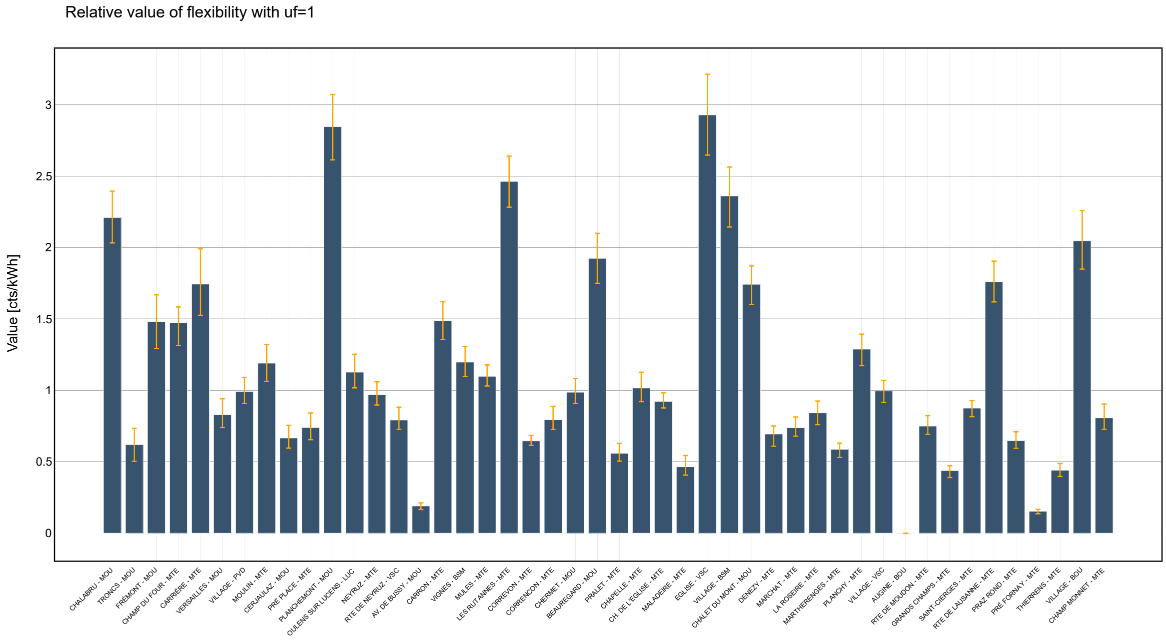

Figure 37 Relative value of flexibility for each LV network in Lucens (using calculation approach 1 according to chapter 3.1.1)

Figure 39 shows the results for relative values of flexible energy using approach 1 for every LV network in Lucens (described in chapter 3.1.1). 25% of the energy difference between the annual load flow simulation before and after network reinforcement is used here for the calculations.

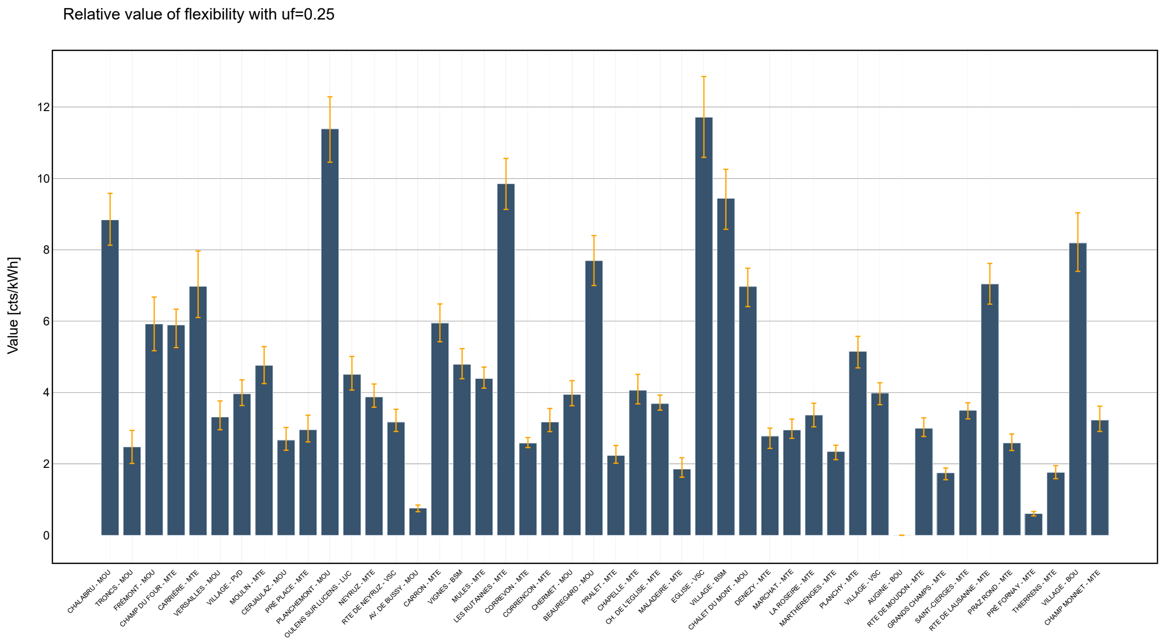

Figure 38 Relative value of flexibility for each LV network in Lucens (using calculation approach 2 according to chapter 3.1.1) for a usage factor of 25%.