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Coordinated utilization of distributed flexibility resources at the network level

Technical report

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D2.4.1 Report describing the developed methodology for coordinated operation of flexibility resources at the network level and the associated results

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Summary

This report presents a methodology developed in the context of the PATHFNDR project, designed to support electricity distribution utilities in efficiently defining and procuring flexibility offered by distributed energy resources such as solar photovoltaics, electrical vehicle charging, electrical heat pumps, etc. connected mainly to the low-voltage electricity distribution grids for grid operation. The proposed approach addresses the challenges of integrating flexibility services into distribution network operation by providing a structured approach to estimate flexibility needs and facilitating the procurement process through a local flexibility market. The approach leverages a local flexibility market to acquire flexibility from end-users (i.e., customers and prosumers), addressing seasonal variations, daily operational patterns, and uncertainties related to renewable generation and demand.

Following, an actual distribution system is used to demonstrate the methodology for a future scenario of increased renewable generation and demand from heat-pumps and electric vehicles. The first step of the proposed framework is the estimation of flexibility requirements using a combination of historical and forecast data for load and generation. Once the flexibility requirements are identified, the second step is the flexibility dispatch process, interfacing with a local flexibility market where offers from end customers (such as households and prosumers) are collected. Following, an optimization-based flexibility dispatch tool is developed to match flexibility demand with supply, taking into account cost-efficiency and technical constraints, and ensuring that procurement decisions are both economically and operationally viable.

To support longer-term planning, a confidence-based flexibility procurement strategy is introduced. This approach determines the required flexibility quantities by applying statistical confidence levels to forecast uncertainty, allowing DSOs to balance robustness and cost-efficiency and reduce unnecessary daily flexibility activations while securing sufficient flexibility to maintain security in daily grid operation. The methodology supports both season-ahead and day-ahead estimation, equipping DSOs with a robust and forward-looking tool to anticipate and address flexibility needs under varying operating conditions.

The proposed methodology is designed to be generic, practical, and scalable, considering the diversity of Swiss distribution networks. It accounts for the heterogeneity in DSO operational practices and the varying characteristics of network types, ranging from dense urban grids to rural distribution feeders.

Nomenclature

BRP	Balance responsible party
DER	Distributed Energy Resources
DSO	Distribution System Operator
EV	Electric Vehicles
FSC	Flexibility Service Coordinator
FSP	Flexibility Service Provider
HP	Heat pump
LV	Low voltage
MV	Medium voltage
PV	Photovoltaic
TSO	Transmission System Operator
DSO	Distribution System Operator

1 Introduction

1.1 Motivation

The increased penetration of distributed energy resources (DER), such as photovoltaic (PV) systems, and the ongoing electrification of demand, particularly for heating and mobility, are leading to significantly higher loading levels in medium-voltage (MV) and low-voltage (LV) electricity distribution networks. This evolution is driven by the growing adoption of electric heat pumps (HPs) and electric vehicles (EVs), which, while supporting decarbonization goals, also impose considerable strain on existing network infrastructure.

Traditionally designed for relatively stable and predictable load patterns, distribution networks are now facing operational challenges due to fluctuating and often simultaneous demand peaks, exacerbated by intermittent generation from renewable sources. As a result, many MV and LV networks are experiencing load levels that exceed their initial design capacity, raising concerns about congestion, voltage stability, and transformer overloading.

To maintain reliable and secure grid operation while accommodating these changes, Distribution System Operators (DSOs) must explore new strategies that enable dynamic management of available network capacity. Flexibility, particularly when harnessed from distributed resources, presents a viable solution to defer network reinforcements. Effectively utilizing this flexibility requires the development of innovative methodologies that can quantify flexibility requirements and integrate flexibility services into grid operation.

1.2 The role of distributed flexibility in future power systems

Distributed flexibility typically refers to the ability of small-scale, geographically dispersed resources to modulate their power consumption or production in response to signals from electric power distribution and/or transmission system operators. Photovoltaic (PV) installations, battery storage systems, flexible loads such as electric vehicle charging and electric heat pumps are examples to such dispersed resources. The increasing adoption of these distributed energy resources (DER) presents a critical opportunity for enhancing the efficiency, reliability, and economic operation of both distribution and transmission networks. However, effectively using this available flexibility requires new grid operational approaches and market or tariff schemes, that will reflect the operational objectives and the technical constraints of Distribution System Operators (DSOs) and Transmission System Operators (TSOs).

While TSOs typically procure flexibility services in the form of ancillary services for frequency control, balancing, and overall system stability at the national or regional level to ensure that the system is ready to respond to disturbances, DSOs require flexibility to manage daily operation with local grid challenges, such as voltage violations, congestion on feeders, and transformer loading. Unlike TSO flexibility, which generally focuses on balancing the whole system in a more aggregated form, distribution-level flexibility services necessitate a more granular approach that considers specific network topology, local technical constraints, and consumer behaviors.

The goal of this deliverable is to establish a generic, practical and scalable framework capable of (i) identifying flexibility needs, (ii) defining relevant flexibility products, and (iii) enabling DSOs to procure these services from DER owners. Given the heterogeneity of Swiss distribution grids, characterized by a large number of DSOs with diverse operational practices and significantly varied network types, from

densely populated urban grids to sparsely populated rural feeders, it is essential to develop an easily deployable and adaptable methodology. The presented framework considers these differences by providing a local flexibility market framework that will allow DSOs to effectively procure and activate flexibility based on their specific local conditions, operational practices and grid management objectives.

1.3 The scope and the objective of the deliverable

To address the challenges outlined in Section 1.1, this deliverable presents a methodology for efficiently defining and procuring flexibility within distribution networks. The primary objective is to develop a framework that allows DSOs to identify their flexibility needs, define appropriate flexibility products, and interact with or manage a local flexibility market mechanism to secure flexibility from their customers.

The proposed methodology is designed to be generic, practical, and scalable, considering the diversity of Swiss distribution networks. It accounts for the heterogeneity in DSO operational practices and the varying characteristics of network types, ranging from dense urban grids to rural distribution feeders. By incorporating flexibility requirements directly into the grid management strategy, the framework aims to support DSOs in mitigating the challenges associated with cable overloading, voltage violations, and transformer loading.

The deliverable also demonstrates the application of this methodology in an actual distribution system, with representative future scenarios characterized by increased PV generation, electrified heating, and electric mobility. This practical demonstration serves as a validation of the approach, showcasing how flexibility can be systematically integrated into local grid operations.

2 Options of flexibility services and products

2.1 Sources of flexibility and flexibility services

Flexibility services are essential for maintaining stability, reliability, and efficiency of the power system. These services are enabled by various devices and systems and can be categorized into three main groups as shown in Figure 1: energy demand, energy generation, and storage units. Each group plays a critical role in providing the necessary flexibility to support the time-variant needs of the grid [1].

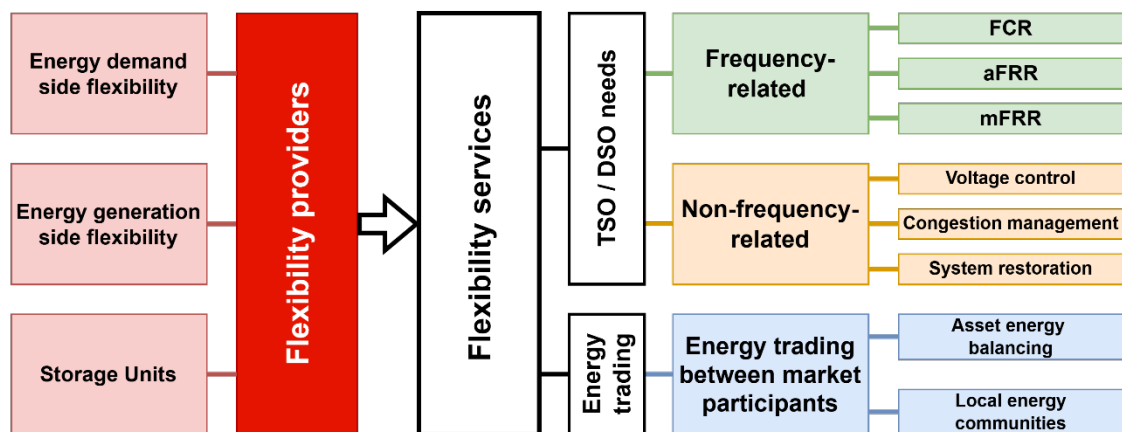


Figure 1. An overall representation of flexibility habitat. Frequency related services are required by TSOs. FCR: Frequency containment reserve, aFRR: automatic frequency restoration reserve, mFRR: manual frequency restoration reserve.

Flexibility providers on the energy demand side: This category includes devices that consume energy and can adjust their consumption. Key devices are electric vehicles (EVs), household appliances, and power-to-heat installations, such as heat pumps and air conditioning units. These devices, whether used in commercial or private context, offer varying capacities and types of flexibility services.

Flexibility providers on the energy generation side: This group consists of energy generation units that can adjust their output to meet the demand. Key providers include combined heat and power (CHP) plants, photovoltaic (PV) systems, wind farms and fuel cells. These generation units, ranging from commercial-scale installations to residential setups, provide essential flexibility by modulating their power output. Their ability to respond to signals from system operators ensures a reliable and stable energy supply, integrating renewable energy sources effectively.

Flexibility by energy storage systems: Storage systems are pivotal in the decarbonization of the energy system and the provision of flexibility services. This category includes private and commercial large- and small-scale electrical storage systems (i.e., battery energy storage system – BESS), pumped hydro storage plants, and run-of-river hydro plants with pondage.

BESSs offer rapid response capabilities and bidirectional flexibility (i.e., acting as a generator or as a demand), making them excellent candidates for real-time grid balancing. Pumped hydro and run-of-river hydro plants with pondage provide sustainable and reliable flexibility, supporting the storage and generation of renewable energy. In addition to the active power flexibility that can be flexibly offered, the storage units can support the nodal voltage fluctuations by easily providing reactive power capabilities.

Besides activating large power plants and consumers, the flexibility given by the aforementioned providers can be utilized to stabilize the energy system and ensure efficient operation, enabling and accelerating the integration of renewable energy sources.

Flexibility in power systems can be classified based on the type of **resource**, the **controllability** of the load or generation, and the **timeframe** in which the response is delivered. For this work, we distinguish between controllable loads, such as electric vehicle (EV) chargers, batteries, or industrial demand response, and non-controllable loads, which represent a share of the consumption that cannot be influenced. Flexibility types can be categorized depending on how flexibility is provided: **active power modulation** (i.e., increasing or decreasing the amount of consumption or generation), **capacity limitation** (i.e., capping maximum usage), **energy shifting** (e.g., load reduction at peak and consumption later), **reactive power modulation** (i.e., adjusting the magnitude and the direction of the reactive power for voltage regulation). The framework proposed in this deliverable focuses on the estimation of flexibility needs of the distribution system over different horizons. Based on these requirements, relevant flexibility products are defined and procured through a local flexibility market mechanism. The proposed integrated approach allows the adaptation of flexibility procurement strategies to the specific characteristics and needs of each network, the available resources and specific operational conditions.

The concept of “**local flexibility markets**” refers to all market-based procurement of flexibility services by DSOs. In these markets DSOs typically are the buyers of flexibility services. However, other entities, such as TSOs or balance responsible parties (BRPs), may also participate in procuring flexibility services, depending on the specific context. An overview of the different types of flexibility services and potential buyers is presented in Table 1.

This deliverable focuses on the procurement of flexibility through a local market mechanism. Nevertheless, it should be noted that participation in the local flexibility market is one of several options available to flexibility providers. Depending on the regulatory framework and individual preferences (DSO and/or FSP), FSPs may also choose to sign up for dynamic tariffs or enter into bilateral contracts directly with the DSO or BRPs. However, a customer cannot participate in the local flexibility market and have an active bilateral contract for the same service period simultaneously. This is to ensure clear and non-overlapping commitments.

Table 1 Mapping of the flexibility types with corresponding buyers of flexibility services

Flexibility service	Buyer of flexibility services		
	DSO	TSO	BRPs
Congestion management (distribution system)	X		
Voltage control (distribution system)	X		
Reliability enhancement (distribution system)	X		
Grid investment deferral (distribution system)	X		
Frequency control/ system balancing		X	
Congestion management (transmission system)		X	
Portfolio optimization			X

2.2 Role of Flexibility Service Coordinator (FSC)

Given the complexity and the heterogeneity of distribution networks, especially in Switzerland, the procurement and the activation of flexibility require a well-coordinated approach. An entity, which will be hereinafter referred to as the “Flexibility Service Coordinator” (FSC) is envisioned as a neutral and centralized market entity responsible for orchestrating the interaction between stakeholders involved in the provision and request of flexibility. The FSC receives flexibility requests from DSOs and matches them with flexibility offers from DERs, such as aggregators or flexible asset owners. DSO flexibility requests can arise from critical loadings of cables and transformers, nodal voltage violations, or system-level balancing needs.

Acting as a market operator, the FSC ensures efficient procurement and dispatch of flexibility resources, taking into account the location, the type, and the available timeframe of the flexibility resources. It is also responsible for clearing the market, ensuring non-discriminatory access and coordination among parties. It should be noted that the FSC role may be assumed directly by the DSO. Additionally, flexibility services may also be procured through bilateral contracts outside a formal market structure, depending on the specific regulatory framework or local agreements. The FSC ensures non-discriminatory access and coordination among all parties involved, without implying direct control over assets by the operators.

This deliverable focuses on DSO-driven flexibility procurement. Note that the concept of FSC can also be extended to coordinate also with TSO needs for system-level services [2] [3]. In such cases, it is essential to ensure that local grid constraints are satisfied before giving approval to flexibility providers to offer services to TSO. This prioritization can be carried out either by the FSC, acting as a neutral and independent entity, or by the DSO itself. However, the coordination of TSO flexibility requests and activations lies beyond the scope of this deliverable.

FSC as a centralized neutral entity can coordinate between:

- DSOs (local grid constraints),
- TSOs (bulk system balancing, voltage control), and
- FSPs (flexibility providers across various sectors),

while it receives and processes the following:

- **Flexibility requests:** Provided by system operators, including the bid amount, price, location, type, direction, and timeframe of needed flexibility.
- **Flexibility offers:** Provided by FSPs, including the offered quantity, price, location, type, direction, and timeframe of offered flexibility.

2.3 Three-Step Flexibility Procurement Process

The proposed flexibility procurement process follows a structured, three-step approach to ensure that distribution network operators efficiently and effectively manage local grid constraints through a local flexibility market. At the core of this process lies the concept of flexibility requirements, which represent the DSO's estimation of the amount, location, and timing of flexibility needed to resolve anticipated network constraints. These requirements are defined in advance, based on network analysis and forecasts, and serve as input to the procurement in the local market.

In the first step, the framework provides a methodology for estimating the flexibility requirements of the distribution network over various planning horizons. This process combines AC power flow simulations with sensitivity analyses, allowing DSOs to quantify the amount, location, and timing of flexibility needed

to resolve anticipated grid constraints based on forecast scenarios and network topology. This involves the following:

- identifying the spatial requirements: specific grid locations (e.g., buses or feeder segments),
- estimating the required flexibility quantity (i.e., in MW),
- identifying the temporal requirements (i.e., the season, day, time of the day and duration when flexibility is needed), and
- defining the relevant product types and characteristics, such as the activation period and the desired flexibility timeframes (monthly, seasonal, daily, or hourly).

In the proposed framework, once these parameters are defined, DSO would submit the estimated flexibility requirements to the FSC. Additionally, DSO would determine a time window for flexibility service providers (FSPs) to submit their bids. It is noted that while such an approach is not yet enabled by current regulation, the proposed framework envisions the FSC as the sole entity responsible for coordinating market-based procurement of flexibility services. In general, a DSO can still provide its customers with other options such as dynamic tariffs and bilateral contracts as other flexibility options.

In the second step, the framework requires these identified flexibility requirements to be translated into specific flexibility products with well-defined characteristics. Two main product categories are considered as part of this work: (i) Baseline Services which are based on deviations from expected consumption or generation profiles and (ii) Capacity Limitation Services which directly cap maximum power usage. This classification ensures that the procured flexibility aligns with both the operational needs of the grid and the capabilities of potential flexibility service providers.

In the third step, the framework focuses on the procurement of flexibility from end-customers through a local market mechanism. Upon receiving the flexibility requirements from the DSO, the FSC initiates the market clearing process. First, the FSC identifies and contacts suitable FSPs, informing them about the procurement opportunity and the bidding window. Following, FSPs submit their flexibility offers, detailing their available capacity, activation prices, and technical parameters aligned with the DSO's specified requirements.

Once the submission window for the flexibility offers closes, the FSC clears the market by using an optimization-based approach and selects the optimal set of flexibility resources capable of addressing the DSO's stated requirements at minimum total cost. This structured approach ensures transparent, economically efficient, and technically sound procurement, facilitating precise alignment between flexibility service offerings and the DSO's actual flexibility needs for grid management.

The operation of the FSC is designed in a manner to be operated along multiple time horizons, reflecting the diverse needs of the grid and the different levels of adoption readiness of DSOs to engage with flexibility markets. Examples of time horizons are as follows:

- long-term (i.e., monthly, seasonal, or yearly),
- short-term (i.e., week- or day-ahead), and
- near-real-time (i.e., intra-day hour-ahead).

In the long-term timeframe DSOs may facilitate the procurement of capacity limitation products, allowing DSOs to secure grid security through forward contracting. In the short-term timeframe, the FSC supports power product procurement, enabling proactive congestion management based on forecasted conditions. Finally, in near-real-time, the FSC coordinates the activation of flexibility resources, responding to real-time grid measurements or updated forecasts. The specific timeframe each system operator adopts depends on the observability of the grid, the forecast accuracy of generation and demand, and specific infrastructure planning processes, making the FSC a flexible, adaptable tool across heterogeneous regions. Table 2 summarizes the timeframe of the potential flexibility markets

along with their use-cases and the product types. Finally, DSO objective in resorting to flexibility markets are mapped to each flexibility market.

Table 2. The timeframe, use-case, type of the product of the flexibility markets and the primary objective of the DSO

Timeframe	Use Case	Product Type	DSO objective
Seasonal/Monthly	Grid capacity constraints, asset deferral	Capacity Limitation Products	Long-term planning
Day-Ahead/Intraday	Forecasted grid stress, forecasted overload	Power Products	Operational planning

3 Proposed Approach for Flexibility: Requirements & Procurement

3.1 Introduction

Flexibility management in distribution networks is becoming increasingly essential as the integration of DERs grows. The increasing complexity and variability in network conditions necessitate adaptive and efficient operational strategies to ensure system security and reliability. The proposed framework addresses these challenges through three main components that are presented in this chapter, demonstrating how a DSO would operate in practice, following a sequence from planning to procurement.

The framework begins with the methodology for defining the required flexibility quantities, considering forecasted network conditions and topological characteristics of the radial distribution network. This is achieved based on (i) performing AC power flow simulations and (ii) using sensitivity matrices to accurately allocate flexibility to specific network locations. Once the requirements are identified, the second step involves defining the flexibility products and their main characteristics. This report defines and compares two main categories of flexibility products, namely **Baseline Services** based on deviations from expected consumption or generation profiles and **Capacity Limitation Services** which impose fixed limits on power consumption or generation. The third component focuses on the procurement of flexibility from end-customers through a local market, ensuring that the dispatch of flexibility is both cost-effective and technically feasible. To enhance the robustness of this process, a confidence-based procurement strategy is also introduced, enabling DSOs to plan flexibility needs ahead of time accounting for forecast uncertainties.

3.2 Estimating Flexibility Requirements: Methodology

The proposed methodology for estimating the flexibility requirements in power distribution networks incorporates historical data and forecasts of network loads, generation and operational conditions. The forecast scenarios and the historical data are used to perform AC power flow simulations and identify the potential network violations, such as distribution line overloadings or voltage violations or transformer overloading, or when the critical thresholds determined by the utility for the aforementioned grid violations are to be reached, if additional flexibility is not activated. Based on the results of the AC power flow simulations, the DSO can estimate and quantify the flexibility needs as the amount and the direction of active power adjustments.

The requirements need to be localized within the network and mapped to specific flexibility service providers. To achieve this, the proposed methodology incorporates a sensitivity matrix (i.e., power transfer distribution factors, PTDFs) that identifies the relationship between power injection/withdrawal at each bus and power flows on each cable, and evaluates whether and how much power injections/withdrawals at each bus affect the line flow of each line. In radial distribution networks more specifically, this matrix is derived considering that only the downstream buses of each line can affect the power that flows through the line.

By applying this mapping, the DSO can allocate the required flexibility volumes to the relevant bus groups in a way that reflects the actual grid topology and avoids redundant or misaligned procurement. This structured allocation forms the basis for defining locational flexibility products and supports the subsequent market-clearing process.

Figure 2 presents the concept of the flexibility requirement estimation process in radial distribution networks. The figure illustrates the sequential steps taken to identify critical network elements and map the required flexibility to downstream nodes while considering potential overlaps and interdependencies.

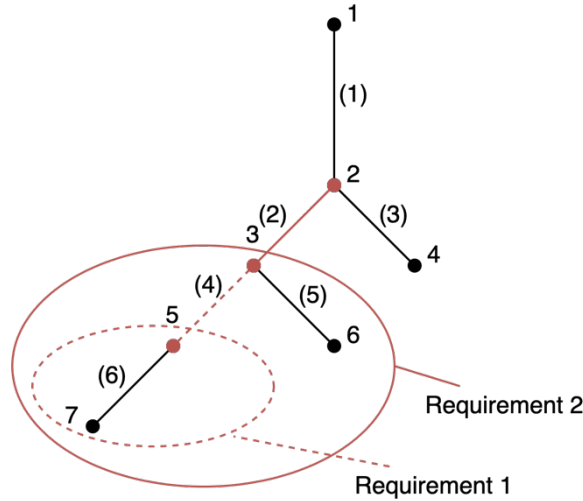


Figure 2 Conceptual framework to estimate DSO flexibility requirements

Algorithm: Qualification of DSO flexibility requirements

Input:

- Network topology (i.e., connectivity) information (buses, lines)
- Steady-state electrical parameters of network components
- Set of power flow results for selected proliferation levels of DERs
- List of subscribed flexibility service providers and static information (location, installed capacity)

Step 1: Detect critically loaded branches and determine initial flexibility requirements

- Iterate over all branches of the network and over power flow results for all the time-periods that are considered, extract the critical loading values as well as the times and locations where they occur (i.e., worst case loading for robustness or a percentile depending on the risk requirements of the DSO)
- For each network constraint (e.g., overloaded branch) and time of occurrence (e.g. between 10:00 and 14:00 o'clock on weekdays during summer), a flexibility requirement is defined and associated with the set of downstream nodes that can influence it.
- For each requirement, determine the set of downstream nodes and identify the FSPs that are technically eligible to offer the corresponding flexibility services (for example, households or grid connection points with PV or with EV charging infrastructure)
- Store each initial requirement

Step 2: Adjust flexibility requirements based on their dependencies

- Because flexibility requirements may share overlapping downstream nodes, flexibility allocation begins from the furthest downstream violated network lines and moves upstream toward the substation. This ensures that flexibility provided by downstream nodes is only counted once and is not double-allocated to multiple constraints.
- The initially identified flexibility requirements are sorted in ascending order based on the number of downstream nodes (i.e., begin with the furthest downstream violated network line and moves upstream)
- Iterate over sorted flexibility requirements:
 - For each requirement extract power requirement and downstream nodes
 - Check if any earlier processed requirements share downstream nodes
 - If shared nodes exist, adjust the flexibility requirement by subtracting the flexibility already allocated to the previous requirements.
 - Ensure that the updated flexibility requirement is non-zero.

For meshed distribution networks, the sensitivities (also known as power transfer distribution factors – PTDFs) will be used, which contains the information of the impact of active/reactive power injection/withdrawal at a given node on each branch.

Note that when a local flexibility need is procured through a market, the loads located on the downstream nodes may have very high market power. In the worst case, there may be only one single supplier of flexibility, who could then ask almost any price for his services (e.g., a farmer with lots of PV, whose injections are causing the grid overloads for whose reduction). This problem can be avoided by pre-assessing the FSPs and setting a maximum limit for the flexibility payments in the flexibility market.

3.3 Flexibility products: definition

Within the context of flexibility procurement from DERs, two main categories of products are identified: **Baseline Services** and **Capacity Limitation Services** (See Table 2). Each product type has distinct characteristics, implementation methods, and verification processes which are outlined below.

3.3.1 Baseline Services

Baseline services refer to flexibility products defined as deviations from a pre-determined reference profile, known as the "baseline" [4]. The baseline typically represents the expected consumption or production pattern of FSPs if no flexibility activation takes place. Baseline calculation methods vary widely and can involve calculating average consumption from historical data, performing regression analysis to predict expected usage, applying interpolation techniques to estimate values between data points, using machine learning models to forecast consumption patterns, or combining multiple approaches into hybrid methods. The specific baseline methodology is typically agreed upon between the DSO and the FSP and may also be defined by the market rules. The choice of baseline methodology can significantly influence the transparency and fairness of flexibility remuneration [5] [6]. Methods that rely exclusively on an FSP's own historical data may incentivize baseline manipulation, as providers could intentionally alter their pattern to increase the measured volume of flexibility. To mitigate this, gaming detection methods are proposed for baseline methodologies, that compare the results with similar providers. As an example, baseline calculation methods such as using statistically relative robust metrics such as long-term moving average (e.g., the median or the maximum of 3-year moving average of consumption data) of the customers in the same customer group (e.g., H4 households with up to 4'500 kWh/year consumption, C5 commercial customers with up to 500'000 kWh/year consumption) will decrease the risk of manipulations. It is noted that the selection of the baseline calculation methodology is not within the scope of this deliverable.

When a DSO identifies a flexibility requirement, it publishes a service request specifying the amount of power regulation needed, the activation period, and the location within the distribution network. Interested FSPs submit bids based on their available flexibility and baseline estimations. Upon selection,

an FSP provides flexibility by adjusting its actual consumption or production from the defined baseline level during the service delivery window. Verification of service delivery involves comparing metered data during activation against the predefined baseline profile.

Despite their common use, baseline methods face challenges such as complexity, lack of transparency, incentives for baseline manipulation (gaming), and limitations in accommodating continuous control actions. These challenges highlight the need for robust baseline definition and validation mechanisms. It is emphasized here that in distribution networks (especially in low voltage networks), the DSO must have a central role to determine (i) how much the maximum price is to be paid to those who provide flexibility through a flexibility market, and (ii) who can provide flexibility simultaneously to TSO and the amount of the flexibility, so that the operational constraints of the distribution grids are respected and mid-term and long-term infrastructure planning can be effectively performed.

3.3.2 Capacity Limitation Services

Capacity limitation services impose explicit limits on the maximum permitted consumption or production of FSPs during specific periods, thereby directly restricting their peak power generation or demand. Products for capacity limitation services are particularly valuable for preventing overload conditions [7]. For example, they can be used to limit the cumulative load served by a transformer, reduce the peak demand on a feeder segment, or limit the total injection from a cluster of DERs during high production periods.

Under the concept of capacity limitation, the flexibility capacities of individual providers are typically defined during a pre-qualification or contractual phase. When grid stress (i.e., critical loading of cables and transformers, nodal voltage magnitudes approaching critical levels defined by standards such as DIN EN 50160) is anticipated, the DSO specifies the required consumption limit in kW and activation timeframe. FSPs respond by maintaining their power consumption within the cleared contractual limits throughout the activation period. The advantage of products for capacity limitation is that the verification is straightforward, relying on metered data confirming compliance with the contractual maximum power level. The concept is similar to and in line with the recommendations in [8], proposed for TSO-level services.

Capacity limitation products resemble capacity subscription models where end-users agree on maximum demand levels with DSOs in exchange for remuneration during the agreement period. However, if the need by DSOs for capacity limitation products is high, market-based clearing mechanisms become necessary to avoid discrimination and ensure fair and efficient allocation of flexibility. There can be cases where the flexibilities offered by the FSPs are less than the required flexibility by the DSOs. The DSO requires flexibility because either it can avoid infrastructure investment by resorting to flexibility or it can postpone the investments because the time needed for reinforcing the grid is long. Therefore, the utility will not allow any “congestion” in the networks. That is why “critical loading” level is defined, which is less than the actual thermal limits for ampacity of the cables and transformers. Thus, in the case when insufficient amount of flexibility is offered, this shall not jeopardize the operational security, however, if this happens on a regular basis, the DSO will expedite the grid reinforcement process.

3.4 Procuring Flexibility: Methodology

Once the flexibility requirements are identified, flexibility procurement is performed, through which the interfaces with the local market where flexibility offers from end-customers are managed. For this purpose, a tool that handles the complexities of matching flexibility demand with supply, ensuring that the procurement is both cost-effective and operationally viable, has been developed within PATHFND and described hereafter. The tool comprises several key components, to facilitate market participation, procurement optimization, and network analysis.

- *Market Participation:* End-customers can participate in this market by submitting offers through the platform that details the flexibility they can provide, including parameters like available capacity, duration, and price. These offers are then aggregated and evaluated based on the current grid needs.
- *Procurement Algorithm:* The core of this tool is an optimization model, typically implemented using advanced mathematical programming techniques such as linear programming. This model considers various constraints and objectives, striving to minimize costs while fulfilling the grid's flexibility requirements. The optimization process involves:
 - Creating a Network Graph:* Represents the grid with nodes and branches incorporating the branch capacity limits and branch (ampacity) loadings.
 - Sensitivity Analysis:* Assesses the impact of potential flexibility activations on the network, identifying critical areas that could benefit from specific offers.
 - Offer Matching:* Dynamically matches offers to requirements based on location, quantity, and other attributes, ensuring that the most suitable resources are utilized.

3.4.1 Confidence-based flexibility procurement

The management of flexibility in distribution networks requires adaptable approaches that can efficiently balance long-term planning with short-term operational practices. Achieving this balance depends on the following 3 pillars (i) managing uncertainty, (ii) integrating risk-aversion processes, and (iii) ensuring economic efficiency. As distribution networks evolve and grow in complexity, DSOs are expected to implement adaptive and efficient operational strategies. These strategies should maintain system security, even under unexpected load or generation scenarios, while maintaining economic viability.

To effectively address these aspects, this section introduces a confidence-based flexibility procurement strategy built upon the previously presented tools for estimating the flexibility requirements. The proposed approach enables DSOs to determine long-term required flexibility volumes, while incorporating confidence levels that influence the procurement process. By adjusting the confidence level, DSO can balance robustness and cost-efficiency, reduce unnecessary activations while securing sufficient flexibility to maintain security in daily grid operation.

The distinction between seasonal and daily operational practices is crucial for determining the role of confidence levels in flexibility management.

- **Season-Ahead Flexibility Procurement:**
This step focuses on long-term planning for flexibility procurement and the proposed framework is based on forecasted seasonal profiles for estimating the flexibility requirements. More specifically the proposed approach involves simulating a 90-day operational period for each season and incorporating long-term forecasts to capture variations in demand and generation and the impacts of such variations on grid operation. The primary objective of seasonal procurement is to secure adequate flexibility that ensures the grid's security and reliability over extended periods. By setting a higher (i.e., conservative) confidence level, the DSO can proactively reserve flexibility, reducing the likelihood of the need for operational flexibility activations but at the same time increasing both his own cost. This approach is particularly useful for addressing predictable, long-term patterns in network conditions, while it is obviously more expensive. The DSO will have a decision space where it can evaluate the level of confidence level along with its operational constraints and grid reinforcement strategies.
- **Daily Flexibility Procurement:**
Despite this season-ahead planning, actual grid conditions can differ due to unexpected demand peaks, generation variability, or unforeseen events. The need for daily flexibility procurement arises when actual grid conditions diverge from the anticipated seasonal flexibility procurement plan. Therefore, the frequency of these activations is directly linked to the chosen

confidence level. A lower confidence level results in less flexibility reserved in advance, increasing the need for real-time adjustments when unexpected conditions arise. A higher confidence level secures more flexibility upfront, leading to fewer activations, as the majority of anticipated conditions are already covered.

The trade-off between seasonal and daily operations is a key element in flexibility management. While robust, high-confidence planning minimizes daily interventions, it may lead to over-procurement, increasing operational costs. Low-confidence strategies shift the burden to the daily operation phase, requiring more frequent interventions to ensure secure grid operation.

4 Application & Results

4.1 Overall description

In this section the proposed flexibility procurement and dispatch framework is demonstrated and validated using real low-voltage grids in Switzerland, representing both urban and rural areas.

The simulations rely on synthetically generated time-series data for household electricity demand, EV charging, solar PV generation, and HP operation. These time-series were produced using a modeling approach originally developed as part of the DFlex study “Distribution system in 2050: the role of flexibility in the distribution system with increasing digitalization” and further refined in the TDFlex project [9].

Two distinct networks were chosen as representative cases:

- Urban LV Network (Figure 3):
The urban network selected for this analysis includes 20 nodes, connected via 25 branches, and fed by a 1 MVA transformer (22/0.4 kV). The network has radial topology and contains four loops. The underground cables uniformly have a cross-sectional area of 185mm^2 , and the total length of the cables is 3 km. The estimated population of the urban district is 965 residents.

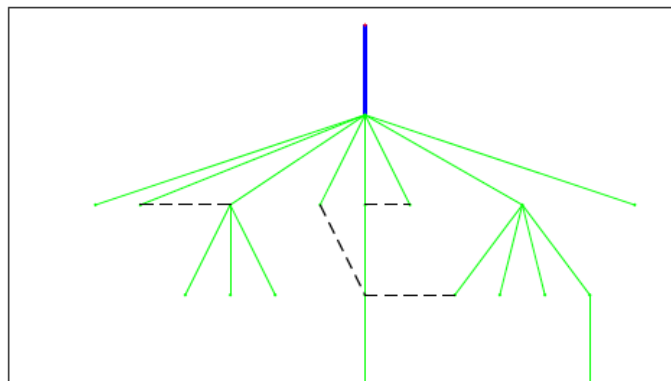


Figure 3 The 0.4-kV urban network

- Rural LV Network (Figure 4):
The rural network is comprised of 102 nodes, connected via 105 branches and served by a 0.63 MVA transformer (10/0.4 KV). The network has radial topology and contains three loops. The underground cables with main feeders have a cross-sectional area of 150mm^2 (1.6 km), and the rest of the cables have an almost equal distribution of 16 mm^2 , 25 mm^2 , 50 mm^2 and 95 mm^2 sections, resulting in a total of 3.8 km underground cables in the district. The estimated population of the rural district is 515 residents.

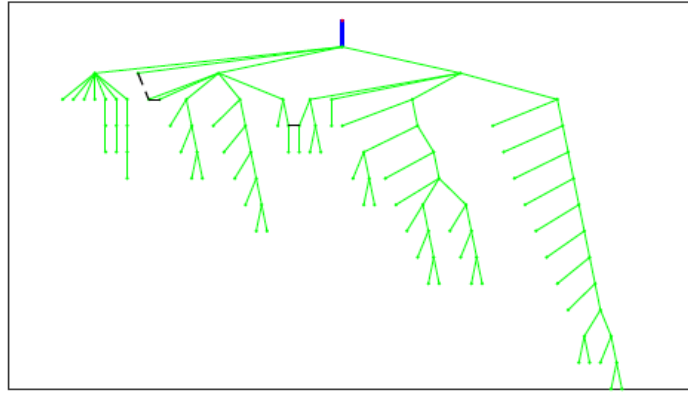


Figure 4 The 0.4-kV rural network

The analysis presented in this chapter is conducted using the proposed two-step strategy for confidence-based flexibility procurement. The long-term flexibility is procured on a season-ahead basis, considering the worst-case forecasts for each season (winter, summer, and transitional periods). Following using the short-term forecasts, the previously procured flexibility products are validated using updated day-ahead forecasts, and, if necessary, additional flexibility resources are procured to address any remaining or unforeseen operational constraints identified closer to real-time.

To illustrate the flexibility needs within each seasonal scenario, the aggregated worst-case generation and demand curves for each season for a future year (e.g., 2040+) with very high DER proliferation are presented in Figure 5. These aggregated time-series represent the combined profiles of conventional residential loads, EV charging, electric HP consumption, and rooftop PV generation at the network level. The figure presents the demand and generation data over a representative three-day period, covering a Weekday, Saturday, and Sunday at 15-minute resolution.

In winter, the aggregated HP demand is increased due to high heating requirements. At the same time, PV generation remains relatively low throughout the day due to reduced solar irradiation, which results in a pronounced net demand during most hours. In contrast, during summer period PV generation is substantially higher, peaking around midday, while HP consumption is also considerably lower, peaking to supply the water heating demand. The transition period (spring/fall) represents a middle ground, where PV output is moderate, and both HP and EV-related demand present daily peaks, especially in the early morning and late evening, matching common commuting and heating patterns.

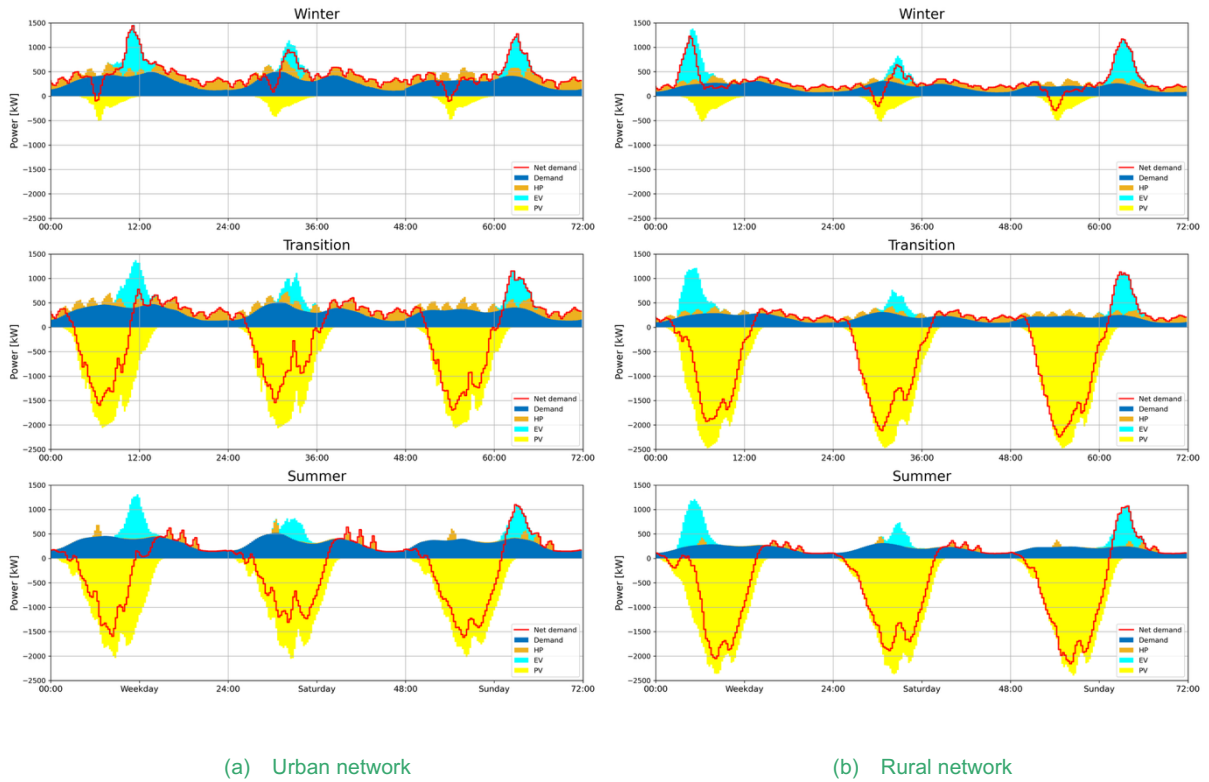


Figure 5 Aggregated demand, generation and net demand for the urban and rural network across different days and seasons

4.2 Results

4.2.1 Season-ahead flexibility

The first stage of the flexibility procurement process involves the season-ahead estimation of required flexibility based on worst-case forecasts of network conditions for each season. Using power flow results from the seasonal demand and generation scenarios, the DSO identifies potential branch (i.e., cable, transformer) critical loadings, computes the required flexibility per line to alleviate the critical loading, and assigns it to downstream buses using a sensitivity-based approach. Note that, “critical loading” is used to describe the loading level of the cables and transformers in daily operation that is tolerated by the utility. The critical loading level for cables and transformers can be different. The thermal ratings of the cables and transformers can be used as well, corresponding to a 100% loading level. Nevertheless, a typical critical loading level used by utilities is between 70 and 80% of the thermal rating of network assets, serving as a safety buffer to prevent equipment from approaching actual overload conditions.

To account for uncertainties in seasonal forecasts, the proposed confidence-based procurement strategy is utilized. The maximum flexibility requirement across the season is determined based on a selected confidence level enabling the DSO to procure a level of flexibility that covers the majority of possible network conditions, while avoiding over-procurement that would increase costs unnecessarily. Comparative results for different confidence levels (e.g., 90%, 95%, and 99%) are presented in Figure 6 for the urban network and in Figure 7 for the rural network to assess how the level of conservativeness affects both the secured flexibility volumes and the need for additional procurement during operation. Each row in the figure corresponds to a different confidence level, illustrating how increasing the robustness of the flexibility requirement impacts the estimated quantities for different seasons.

The plots show the distribution of flexibility requirements throughout the day for different seasons (Winter, Summer, Transition) and day types (Weekdays, Saturdays, Sundays). As the confidence level increases from 90% to 99%, the required flexibility quantities also increase, reflecting the need to account for more extreme scenarios. This allows for a better understanding of how the selected

confidence level influences both the secured flexibility and the potential need for additional procurement during network operation.

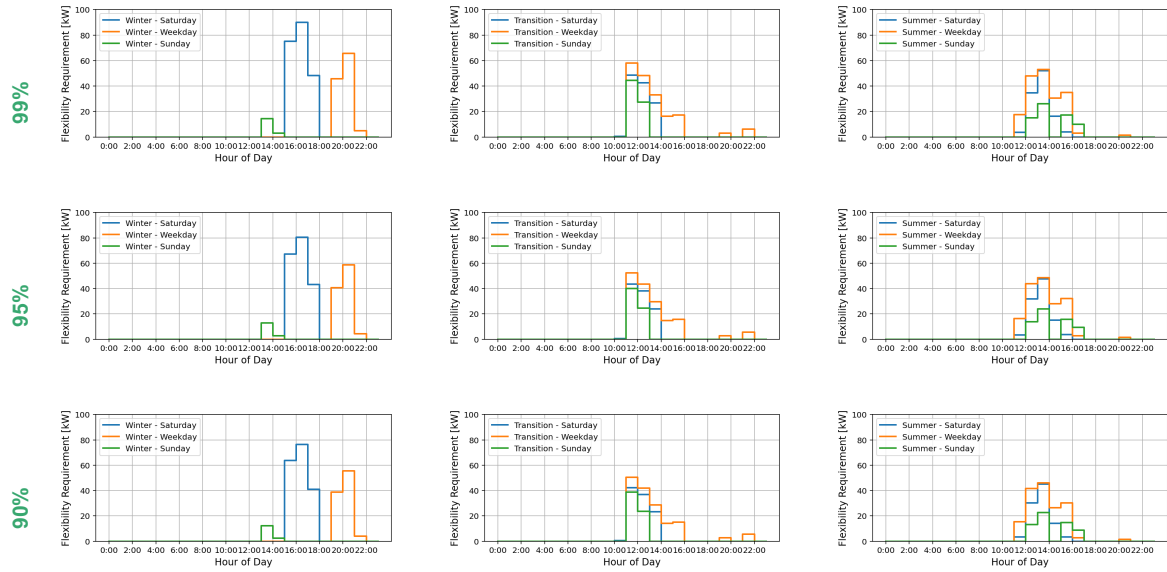


Figure 6 Season-ahead flexibility requirement for different confidence levels for urban network

The two network types reveal notable differences in both the magnitude and temporal spread of the flexibility requirements. In the urban network, flexibility needs tend to be more concentrated within specific hours, reflecting the dense stress of the network within specific hours. In contrast, the rural network the observed flexibility requirement peaks are both higher and more temporally spread out compared to the urban case, especially during the transition and summer season, where variability in local generation and consumption is higher.

The broader and more frequent flexibility requirement for the rural network in Figure 7 may suggest, that the violated network constraints may not be as easily addressed through flexibility procurement alone. Instead, this type of flexibility needs could serve as a signal for the DSO to consider targeted network reinforcements, rather than relying solely on local flexibility markets.

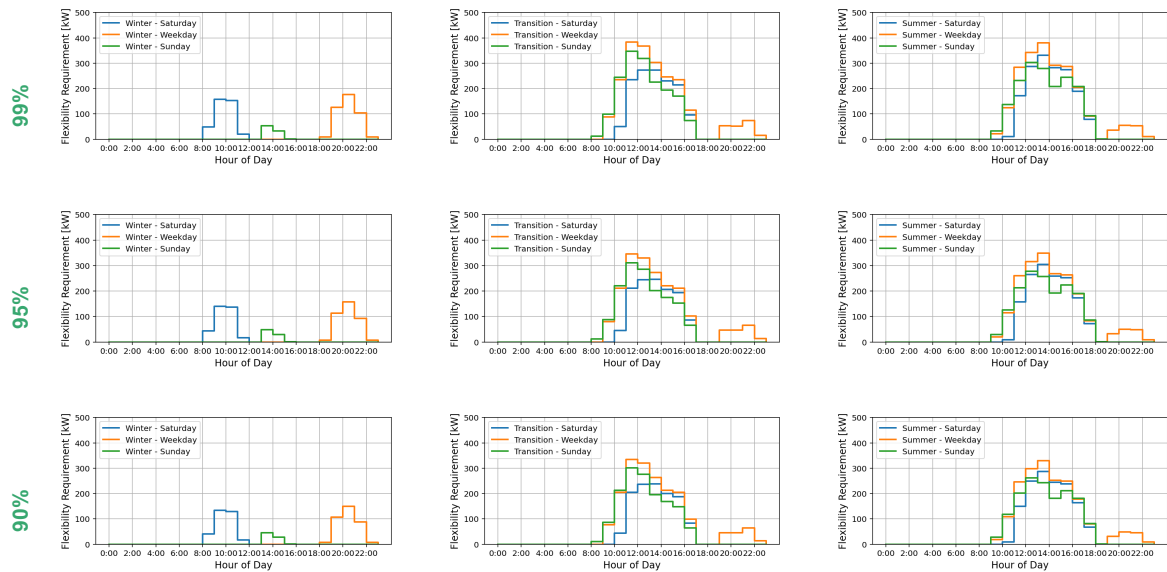


Figure 7 Season-ahead flexibility requirement for different confidence levels for rural network

4.2.2 Day-ahead flexibility

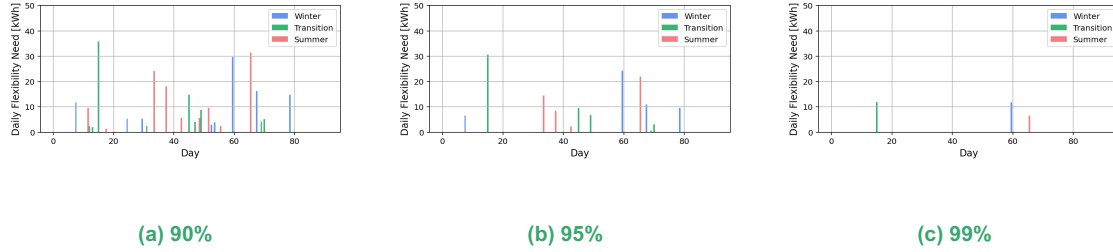


Figure 8 Additional day-ahead flexibility requirement in kWh for different season-ahead confidence levels for urban network

Once the season-ahead procurement is completed, daily operational adjustments are necessary to account for the inherent variability in actual network conditions due to stochasticity in the end-user behavior and/or in weather. As distribution networks evolve, and their operation becomes increasingly complex, DSOs are expected to adopt more adaptive, efficient operational strategies and maintain system security, even under unforeseen load or generation conditions.

In this section, the results of flexibility procurement on a daily basis are presented first, following the season-ahead flexibility procurement performed at different confidence levels. Specifically, we simulate a 90-day operational period for each season, using the season-ahead forecast to reflect variations in demand and generation. Figure 8 summarizes the total daily additional flexibility needs in kWh for three different season-ahead confidence levels: 90%, 95%, and 99% for the urban network. Each subplot shows the days within each season (Winter, Transition, Summer) where the actual flexibility demand exceeded the procured flexibility, and thus additional resources had to be activated. Figure 9 presents the corresponding results for the rural network, enabling a comparative analysis of flexibility needs and procurement between the two network types.

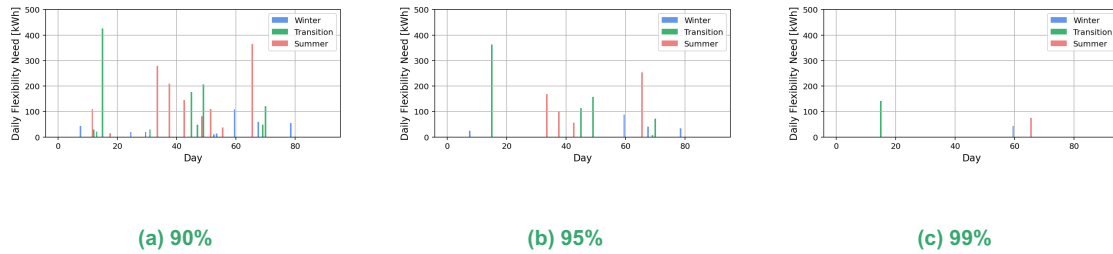


Figure 9 Additional day-ahead flexibility requirement in kWh for different season-ahead confidence levels for rural network

As expected, higher confidence levels lead to fewer daily flexibility procurement, since more flexibility is reserved in the upfront. However, the results also highlight a clear trade-off: lower confidence levels shift the burden of flexibility to the operational phase, increasing the frequency of day-ahead activations. These findings reinforce the importance of combining seasonal flexibility procurement planning with short-term adjustments to ensure grid reliability at minimal cost.

5 Discussion: The Role of Local Flexibility Markets for Deferring Grid Asset Investment

5.1 Introduction

The purpose of this chapter is to discuss and assess the role of local flexibility markets in investment planning activities, specifically in assessing the feasibility of using local markets as a **bridging** solution as **investment deferral** tool. This approach is distinctly different from operational practices, which focus primarily on short-term flexibility procurement. The goal is to investigate whether local flexibility markets can effectively support planning decisions by providing an alternative to grid asset investments. This is achieved by quantifying the annual flexibility requirements under various operational scenarios and comparing the total cost of procuring flexibility through local markets with the cost of traditional grid asset investments.

The approach presented here consists of the following steps:

- **Scenario Definition:** We define multiple operational scenarios that capture varying levels of demand, renewable generation, and flexibility requirements. These scenarios are based on historical data and projected future conditions.
- **Probability Estimation:** Each scenario is assigned a probability of occurrence based on historical frequency for each season and type of day (weekday, Saturday, Sunday).
- **Flexibility Needs Calculation:** For each line and scenario, we calculate the annual flexibility needs by considering scenario probability and the number of days per season.
- **Comparison with Investment Costs:** We then compare the calculated flexibility needs against the cost of potential infrastructure upgrades to determine whether local flexibility procurement is economically justified.

5.2 Definition of Operational Scenarios

For illustration purposes we used the urban grid as presented in Figure 3 in Section 4.1. We defined 10 distinct **operational scenarios** (S1 to S10) to ensure that varying levels of demand and generation across the year are captured. Each operational scenario consists of 3 representative days (Weekday, Saturday, Sunday) for each of the 3 different seasons (Winter, Transition, Summer), and hence a total of 9 representative days. Each sample day is modelled in 15-minute time resolution to accurately reflect the variability in generation and demand profiles. This categorization allowed us to capture the seasonal and daily variability in energy demand and generation.

The analysis of the generated operational scenarios and its stress on the distribution network is presented in Figure 10, Figure 11 and Figure 12. These figures present the variability of solar generation and demand across different scenarios and seasons and their significance for transformer loading and flexibility requirements.

Figure 10 shows the total daily PV production in kWh for weekdays, highlighting how solar generation differs across various scenarios and seasons (Winter, Summer, Transition). PV production is increasing significantly in scenarios with higher solar penetration, especially during the summer months. Additional Figure 11 presents the typical daily profiles of demand, PV generation, and net demand for a summer

weekday in two distinct scenarios (Scenario 5 and Scenario 10). These profiles are depicted with a 15-minute resolution, demonstrating how electricity demand and generation fluctuate throughout the day. The net demand curve reflects the residual load that needs to be balanced through energy exchange via the transformer with the upper system voltage level. The figure highlights the impact of increased PV generation on net demand, demonstrating how high solar output during peak hours can result in reverse flows and additional stress to the distribution system.

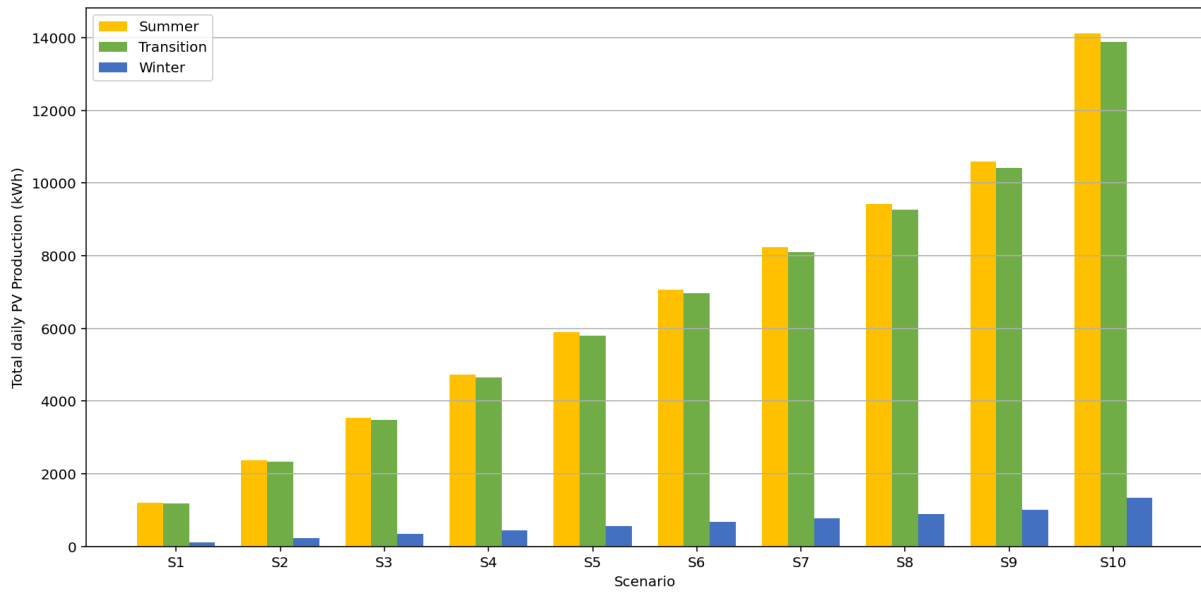


Figure 10 Total daily PV Production per Season and Scenario for weekdays

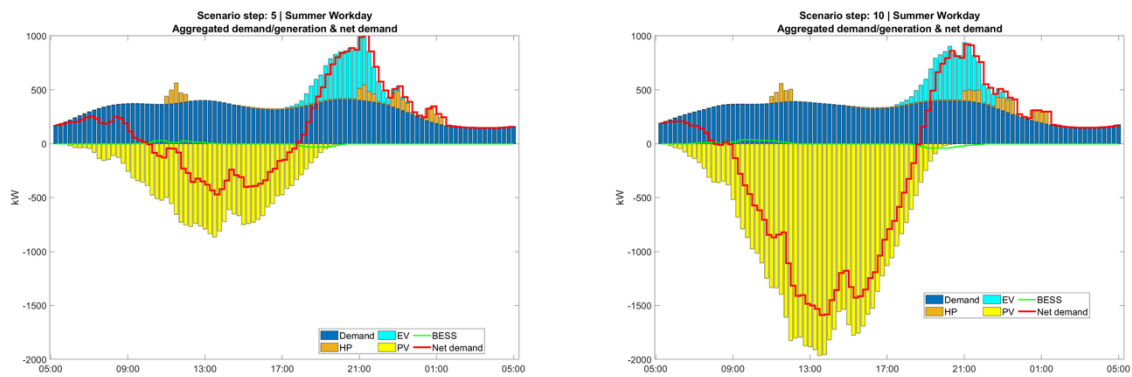


Figure 11 Aggregated demand, generation and net demand for a summer weekday in Scenario 5 and Scenario 10

Figure 12 focuses on the network's operational aspects by showing the loading levels of the transformer for different day types (Weekday, Saturday, Sunday) in Scenario 10. The figure includes data from the seasons and presents the loading levels over the course of each day. This visualization helps to assess how seasonal variations in demand patterns affect transformer loading, revealing potential overload risks during peak solar production. The vertical red dashed lines indicate critical loading thresholds and the thermal limit, to identify potential overload conditions. The graph shows that during the summer, the transformer loading is generally higher compared to winter and transition periods, primarily due to increased solar generation. Winter, on the other hand, exhibits a more gradual decline in loading values, indicating fewer instances of high transformer loading.

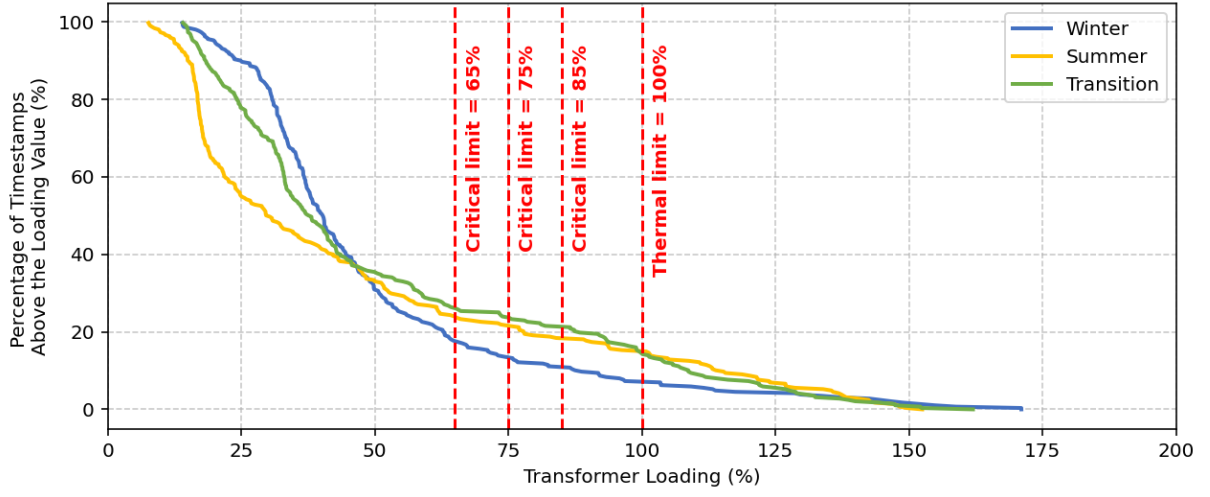


Figure 12 Transformer loading per season for 3 days (Weekday, Saturday, Sunday) in Scenario 10 (3*96 timestamps)

5.3 Probability Estimation

Once different levels of PV generation are taken into account as described in Section 5.2, the frequency of occurrence of each identified operational scenario is calculated based on real PV generation time-series. An actual generation data for one year at a residential PV system in Switzerland is analyzed, using the FEN interactive Webtools platform [10]. This platform provides real-world solar generation profiles, which are used to create daily generation patterns. Each day in the dataset was assigned to one of the ten identified scenarios (S1 to S10) presented in Figure 10, based on its peak daily generation in kW. Seasonal occurrence probabilities were then derived based on the frequency of each scenario within summer, winter, and transition months.

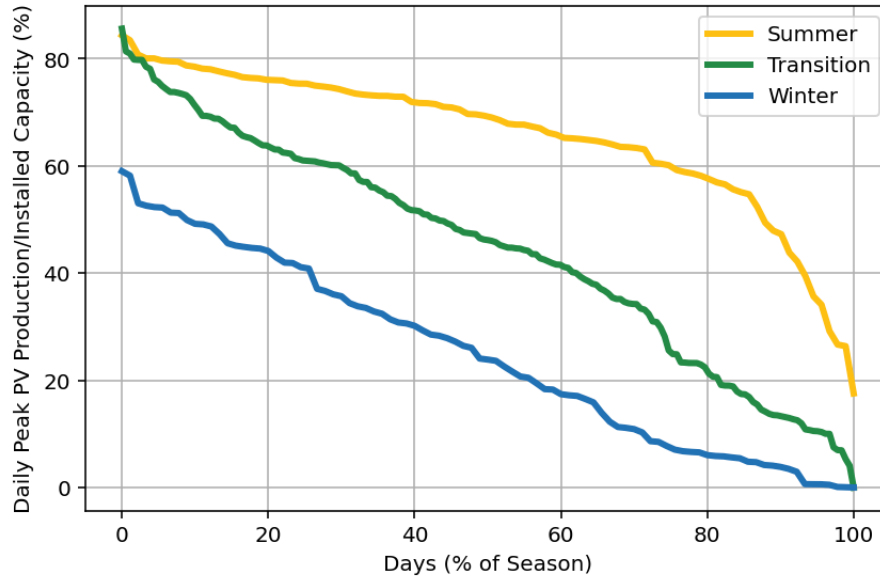


Figure 13 Sorted Daily Peak PV Production per Season (as % of Installed Capacity)

Figure 13 presents the sorted daily PV production of the considered residential PV system for the year 2024, expressed as a percentage of the installed capacity, across different seasonal periods. Each curve represents daily values sorted in descending order, with the x-axis normalized as a percentage of the total number of days in each season. This approach enables a direct comparison of seasonal variability in PV generation.

As observed, summer exhibits the highest and the most consistent daily peak production, with 70% of the days exceeding 60% of the kWp installed capacity. The transition period (spring and autumn months)

shows moderate performance with more pronounced variability, while winter displays the lowest daily peaks, rarely surpassing 60% of the kWp installed capacity and falling below 20% relatively more often.

Figure 14 presents the distribution of scenario probabilities across the three seasons: Summer, Transition, and Winter. These probabilities are determined based on the statistical analysis of daily peak PV production data shown in Figure 13. As observed, high PV generation scenarios (S9 and S10) occur during the summer period, while lower PV generation scenarios (S1 to S4) are more common in Winter. The Transition months display a more balanced distribution across intermediate scenarios (S4 to S8), reflecting the variability inherent during seasonal changes.

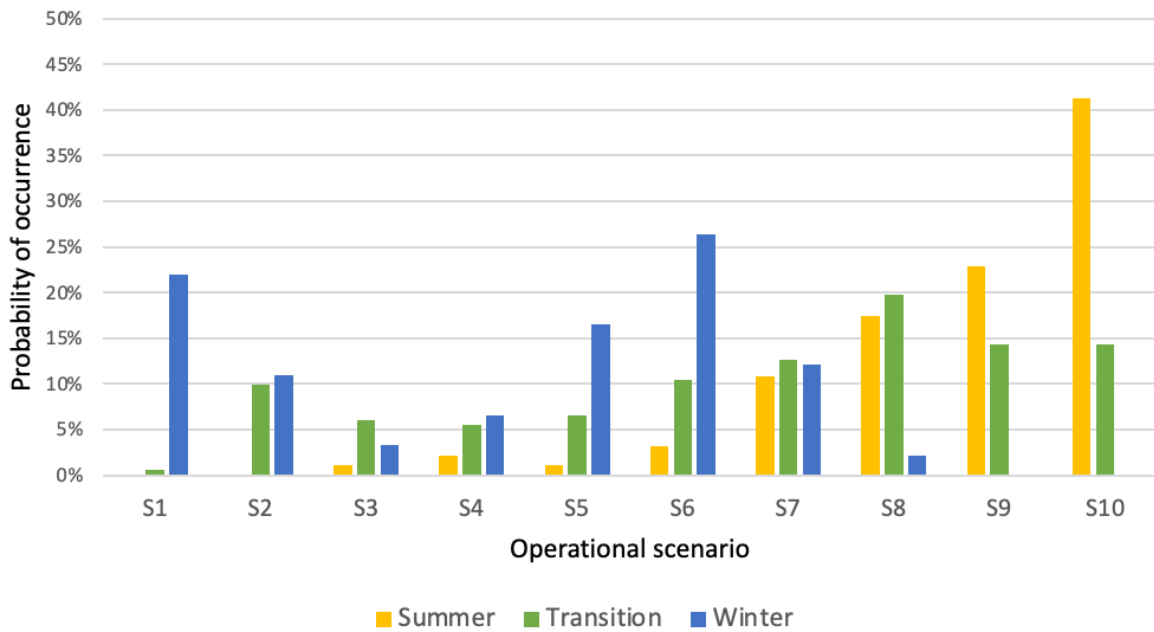


Figure 14 Probability of generated scenarios for each season

5.4 Flexibility Requirements

In this part, we focus on calculating flexibility requirements, by using the methodology presented in Section 3, where the operation of the local market was utilized to address flexibility network violations. The local market results derived for each day and season of the scenarios are used to estimate the seasonal and annual flexibility needs, incorporating the probability estimations derived in the previous step. This step combines the operational practices aiming to estimate the long-term flexibility requirements.

To quantify the annual flexibility needs, we executed the local market operation for each scenario, season, and day type (weekdays, Saturdays, Sundays) as defined in the previous sections. The outputs of these simulations provided us with flexibility requirements for each configuration. Using the scenario probabilities derived from the PV generation data, we aggregated these results to obtain seasonal and annual flexibility needs. Analyzing the results, we identified three distinct pools of nodes where flexibility is requested frequently. These pools were categorized based on their location in the network and are illustrated in Figure 15. The downstream nodes of these three main points form clusters where flexibility requirements are more pronounced. The identified pools are:

- **Pool 1 (Red):** Nodes downstream of Node19-Node8: **Node 8**
- **Pool 2 (Green):** **All nodes** downstream of the transformer (Node17-Node2)
- **Pool 3 (Blue):** Nodes downstream of Node19-Node9: **Node 9**

To better understand the flexibility requirements of these pools, we present a histogram of the daily flexibility needs in Figure 16. This histogram highlights how often specific flexibility levels are required across different days of the year. The results indicate that **Pool 2 (Green)** has the highest frequency of

flexibility needs, while **Pool 3 (Blue)** shows the lowest occurrence. These findings can inform targeted measures for flexibility procurement and network planning.

The frequent and high flexibility needs observed in **Pool 2** indicate that relying solely on flexibility services might not be the most efficient long-term strategy. Instead, the significant and recurring demand may justify considering network reinforcement or infrastructure investment as a more sustainable and cost-effective solution.

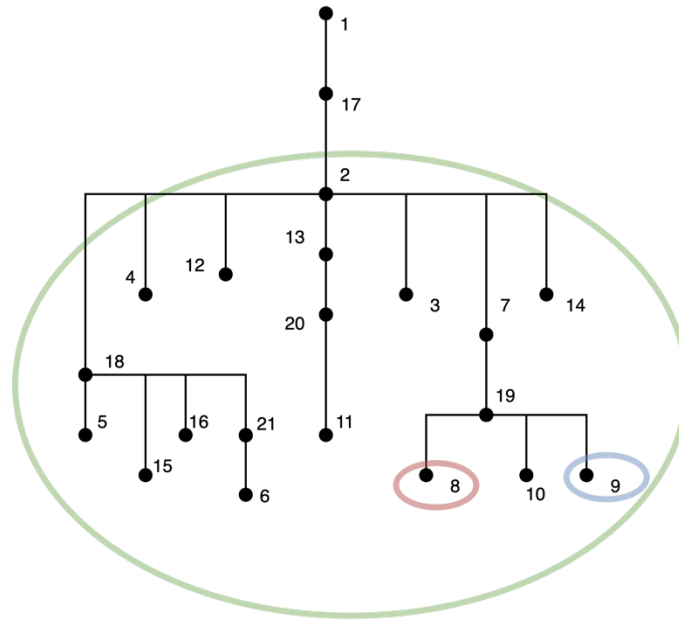


Figure 15 Clusters of nodes with identified flexibility requirements

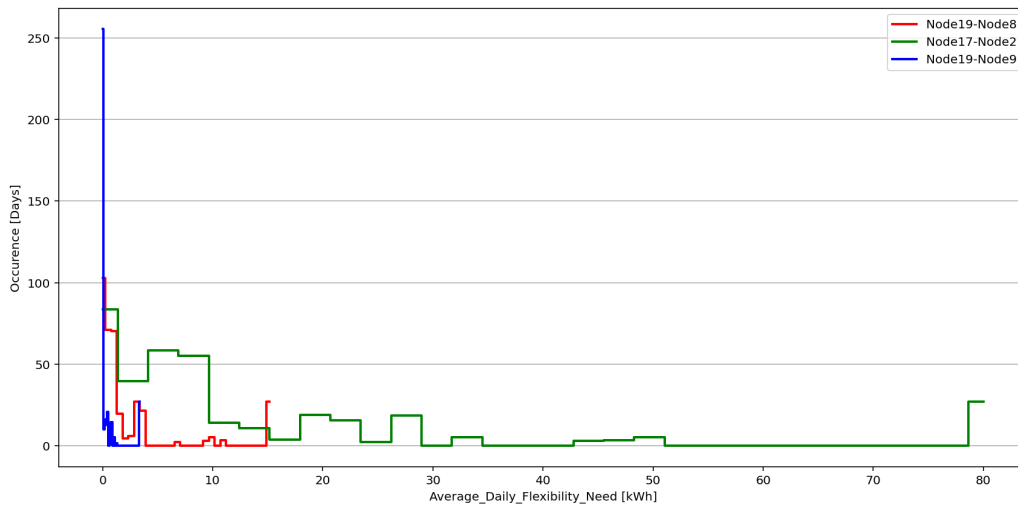


Figure 16 Histogram of total daily flexibility needs in kwh

5.5 Comparison with Investment Costs

Figure 17 shows the annualized cost for doubling the capacity of each of the branches of the test system utilized (presented in Figure 15). The calculation assumes a discount rate of 5% and a branch lifetime of 35 years. Additionally, the annual operating expenses (OPEX) are estimated at 2% of the capital expenses (CAPEX). CAPEX data for typical low voltage 0.44kA cables were used except Branch 17-2 (transformer 1.2 MVA). The branch lengths vary significantly from 0.05 km up to 0.4 km.

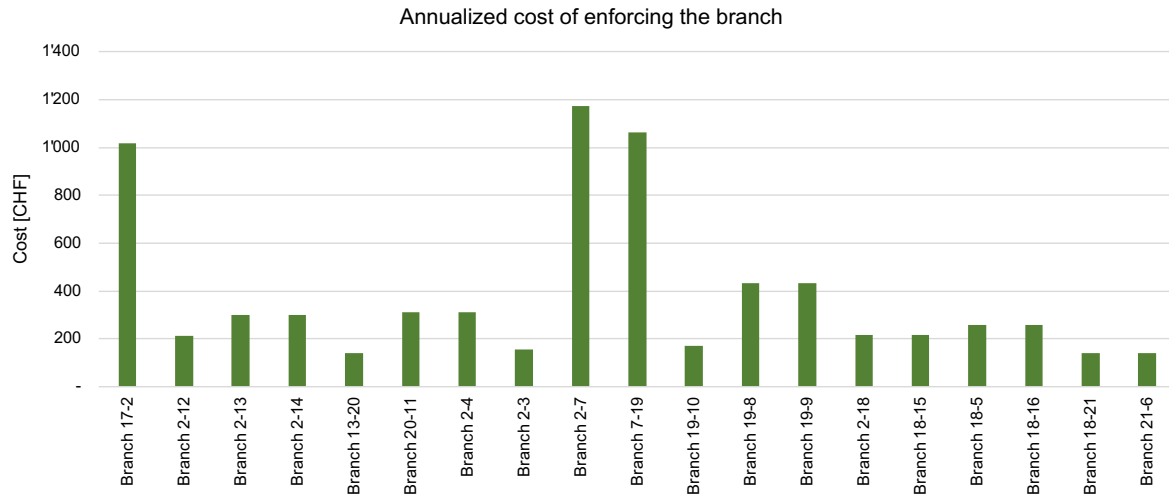


Figure 17 Annualized network expansion cost (includes CAPEX and OPEX). Note that branch 17-2 is the MV-LV transformer, while the rest of the branches are cables.

Using the cost information, the network reinforcements presented in the previous step can be assigned a corresponding annual cost for the utility. It is logical to assume that a flexibility mechanism which allows the utility to save the otherwise required network investments shall not cost more than what the investments would have cost. Hence, the annualized network expansion cost can be seen as corresponding to an annual **budget** that the utility would be willing to spend to procure flexibility services from its customers, if the flexibility services allow to postpone the network investment.

Following this analysis, the flexibility **price limit** is defined as the maximum price (in CHF/kWh) that the DSO would be willing to pay for flexibility services, such that the total cost does not exceed the annualized cost of the corresponding network reinforcement. This price is calculated considering the annualized investment and operational cost of the **avoided upgrade** and the annual flexibility volume required to avoid the upgrade.

$$\text{Flex Price Limit (CHF/kWh)} = \frac{\text{Annualized CAPEX (CHF)} + \text{Annual OPEX (CHF)}}{\text{Annual Flexibility Requirement (kWh)}}$$

A higher price limit indicates that a greater annual budget is available for flexibility procurement, which is typically associated with higher avoided investment costs, and therefore a larger potential economic margin for the DSO.

Based on the results in Figure 16, and the observation regarding the increased flexibility requirements of Pool 2, we have identified two scenarios to evaluate the economic feasibility of the local market for grid asset management deferral.

- **Scenario 1, No Transformer (Branch 17-2) Upgrade:** In this scenario, the network continues to operate without upgrading the transformer, relying solely on flexibility services from Pool 2 to eliminate the transformer flow violations. The resulting flexibility price limit in this scenario is 0.248 CHF/kWh. This limit is relatively low, implying that the DSO should lean towards infrastructure investment, as the budget available for flexibility is limited.
- **Scenario 2, With Transformer Upgrade Scenario:** In this scenario, the transformer capacity is doubled to accommodate the high integration of DERs. The flexibility price limit in this scenario rises to 1.255 CHF/kWh, reflecting the significant capital and operational cost savings margin for the DSO.

The comparison between these two scenarios highlights the trade-off between investing in network infrastructure and relying on flexibility mechanisms. While Scenario 1 offers a lower price limit due to

high flexibility requirements, Scenario 2 provides a more robust long-term solution, reducing the risk of network congestion and ensuring a more reliable grid operation. It should be noted that, to ensure the viability of this approach, further studies are needed to assess the liquidity of the local flexibility market and guarantee that sufficient flexibility resources will be available when required. Additionally, it is crucial to investigate how market liquidity affects flexibility prices, as low liquidity could lead to increased costs, potentially offsetting the expected economic benefits of flexibility procurement.

These findings suggest that while flexibility services can effectively address short-term or moderate demand increases, substantial and persistent flexibility needs, as seen in Pool 2, may warrant a strategic investment in infrastructure upgrades. This example demonstrates how a balanced approach can enable DSOs to optimize both economic and network efficiency, while also considering the potential risks associated with market liquidity and its impact on pricing.

6 Conclusions

The methodology presented in this report offers a structured approach to defining and procuring flexibility offered by the distributed energy resources such as solar photovoltaics, electric heat pumps and electric vehicle charging within electricity distribution networks to distribution system operators (DSOs). By leveraging local flexibility markets, the proposed framework enables DSOs to efficiently address network challenges arising from increased penetration of DERs and electrification of heating and mobility. The integration of flexibility services helps mitigate issues related to voltage violations, overloading of transformers and cables, while offering a dynamic and adaptive solution to evolving network demands.

The practical application of the methodology to a realistic test system demonstrates its capability to handle future scenarios characterized by higher PV generation and increased demand from electric vehicles and heat pumps. The first step of the proposed framework is the estimation of flexibility requirements using a combination of historical and forecast data for load and generation. Once the flexibility requirements are identified, the second step is the flexibility dispatch process, interfacing with a local flexibility market where offers from end-customers (such as households and prosumers) are collected. Following, an optimization-based flexibility procurement tool is developed to match flexibility requirements with offers, taking into account cost-efficiency and technical constraints of the offers, and ensuring that procurement decisions are both economically and operationally viable.

To support longer-term planning, a confidence-based flexibility procurement strategy is introduced. This approach determines the required flexibility quantities by applying statistical confidence levels to forecast uncertainty, allowing DSOs to balance robustness and cost-efficiency and reduce unnecessary daily flexibility activations while securing sufficient flexibility to maintain security in daily grid operation. The methodology supports both season-ahead and day-ahead estimation, equipping DSOs with a robust and forward-looking tool to anticipate and address flexibility needs under varying operating conditions.

The results illustrate how local flexibility, provided by the distributed energy resources in distribution grids and unlocked by flexibility markets, has great potential to reduce or postpone (i.e., defer) network reinforcements. By enabling a more proactive and market-driven approach to network management, this methodology supports the transition towards more resilient and sustainable distribution systems. The insights gained from the application of this framework can guide DSOs in making informed decisions regarding flexibility procurement, daily operation and investment planning, ultimately contributing to the efficient operation of future power systems.

The proposed methodology is designed to be generic, practical, and scalable, considering the diversity of Swiss distribution networks. It accounts for the heterogeneity in DSO operational practices and the varying characteristics of network types, ranging from dense urban grids to rural distribution feeders.

Well-designed local flexibility markets, structured to ensure transparency, competitiveness, and limited market power, offer a cost-effective and scalable solution complementing traditional grid reinforcements. They empower DSOs to proactively manage network constraints under increasing electrification and DER penetration, while unlocking the full potential of distributed flexibility and safeguarding fair pricing and system reliability.

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1	19/05/2025	Revision (1 st and 2 nd)	C. Yaman Evrenosoglu
2	23/05/2025	Revision	Adamantios Marinakis
3	05/06/2025	Revision	Christian Winzer
4	13/06/2025	Revision	C. Yaman Evrenosoglu
5	19/06/2025	Final Version	Nikolaos Savvopoulos

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