# The Role of Flexibility Markets in Maintenance Scheduling of MV Networks

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***Abstract*—Flexibility markets are emerging across Europe to improve the efficiency and reliability of distribution networks. This paper presents a methodology that integrates local flexibility markets into network maintenance scheduling, optimizing the process by contracting flexibility to avoid technical issues under the topology defined to operate the network during maintenance. A meta-heuristic approach, Evolutionary Particle Swarm Optimization (EPSO), is used to determine the optimal network topology.**

***Index Terms*-Flexibility markets, Maintenance scheduling, MV electrical networks.**

## I. INTRODUCTION

Planned maintenance scheduling requires the identification of a topology and time window where the network operates within technical limits, considering forecasted consumption and generation while minimizing clients' disconnections. To avoid service interruptions, DSOs often schedule maintenance outside regular working hours, which can lead to increased labor costs and worse working conditions (for instance, daylight requirement). To ensure these working conditions and comply with regulatory limits on interruption durations, maintenance is frequently scheduled for Sunday mornings, when longer service interruptions are allowed.

The strategic integration of flexibility available on local markets into maintenance scheduling can enable the schedule for regular working hours without implying clients' disconnections, mitigating the effects on end-users.

Literature extensively covers long-term maintenance planning, focusing on identifying the equipment requiring maintenance or replacement. In 2020, a review on maintenance planning in electric distribution systems explored various topics such as reliability indices and uncertainties [1]. However, the potential advantages of incorporating flexibility markets into maintenance planning are not covered.

The work presented in this paper aims at scheduling maintenance already programmed for specific items. In this regard, [2] proposes a tool that generates near-optimal schedules for the tasks to be carried out in one week, assisting the planning engineer at the dispatching service, but it does not consider flexibility services to assist the process. In [3] an approach to preventive maintenance scheduling, using distributed generators and batteries to provide power to nearby loads during maintenance periods, is presented. The paper introduces a method to incorporate maintenance decisions into the model of load served by distributed generators and batteries using topological constraints. However, the network topology reconfiguration is not addressed. [4] includes the network topology reconfiguration approach. However, flexibility is not included as a solution to increase network resilience during maintenance. The concept of uncertainty in photovoltaic generation is included in [5]. It proposes a method for scheduling short-term maintenance of lines in a distribution network with solar power integration, considering the unpredictable nature of solar power generation, as well as other uncertainties such as electricity demand and historical component failure rates. [6] introduces a preventive maintenance scheduling approach for multi-energy microgrids, incorporating precise models for electricity and natural gas to validate simulation outcomes. The study highlights how the optimal interaction between these energy carriers enhances flexibility. It employs sequential maintenance scheduling to improve system resilience but focuses solely on optimizing the operation of system components to maintain energy balance. Unlike the proposed methodology, it does not consider market interactions or network reconfiguration studies.

In [7], an overview of flexibility products and markets identifies a specific gap related to the definition of new system services for DSO that could support network congestion management and maintenance operations.

This paper introduces a comprehensive decision-support tool for maintenance scheduling. Unlike previous approaches, this tool systematically explores a wide range of scheduling options, optimizing the selection of maintenance slots based on network reconfiguration capabilities, clients' consumption and production profiles, and flexibility's availability and costs. This approach ensures a robust and cost-effective scheduling process, fully harnessing the potential of flexibility to maintain network reliability.

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## II. METHODOLOGY

The decision-support tool presented in this paper optimizes the scheduling of planned maintenance activities, incorporating flexibility services from local markets. It assumes that the network operator has prior knowledge of the month and week in which maintenance must occur, along with the expected duration of the activities.

The methodology consists of three main modules: slots definition, network topology optimization, and flexibility solution identification. In the final module, the methodology incorporates interaction with the NODES platform [8], a local flexibility market platform where flexibility can be reserved by node up to three weeks in advance. This platform has been explored and tested as part of the EUniversal pilot project [9].

### A. Inputs

The tool requires input data to assess the network's reconfiguration capabilities, allowing for the creation of an alternative topology after isolating the maintenance area. Additionally, it needs data to analyze the network's technical limits during suitable time slots for maintenance activities. The following inputs are necessary:

- Network characteristics:
    - Network topology during normal operation.
    - Reconfiguration capabilities (detailing switches location, original state, and operability).
    - Technical limits.
    - Transformer taps.
- Forecast for:
    - Consumption and generation profiles for each network connection point.
    - Available flexibility in local markets by the network's nodes.
- Maintenance characteristics:
    - Identification of maintenance area to be isolated.
    - Duration of maintenance tasks.
    - Admissible hours for performing activities, depending on maintenance crew availability and technical requirements as daylight.
    - Predefined timeframe for the maintenance activities (week or month).

### B. Outputs

This tool identifies the optimal time slots within the desired timeframe for conducting maintenance actions. It defines an alternative network topology for operation during these periods and evaluates each solution based on client disconnections and flexibility costs. After assessing all feasible slots, the tool compares them and recommends the best option (or multiple options if equivalent solutions exist), providing the following outputs:

- Optimal schedule of maintenance actions: day and starting time.
- Topology for operation during maintenance, including information about the switches' state changes made to reconfigure the network into the new topology.
- Contracted flexibility, detailing the energy per node and period, along with the respective costs.
- ENS, indicating also the number of clients that could not be served during the maintenance activities with the new topology.

### C. Slots Definition

This module provides information on three critical aspects: suitable slots for performing the maintenance work, ENS and disconnected clients after isolating the maintenance area, and the critical period in each slot.

Using the maintenance characteristics as input, such as duration and operational hours, this module defines the slots suitable for conducting maintenance actions, as in Fig. 1. Once these slots are defined, the next step consists of defining the critical period for each slot, which requires the following steps:

- Identifying disconnected clients after isolating the maintenance area (before reconfiguring the network).
- Calculating the ENS for each period based on these disconnections, by summing of total foreseen load on the disconnected nodes on that period).

The critical period within each time slot, illustrated in orange in Fig. 1, corresponds to the period with the highest ENS. This period is used in the Network Topology Optimization module to assess the network's capability to reconnect clients.

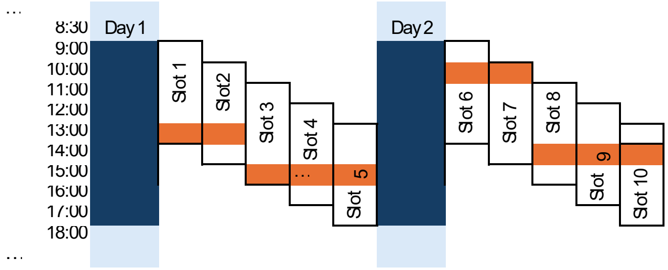

Figure 1. Suitable slots and respective critical periods.

### D. Network topology optimization

The Network Topology Optimization module's main objective is to determine a topology to reconfigure the network during maintenance activities. This module is structured into two main stages, as shown in Fig. 2.

#### 1) Stage 1:

The first step is to identify a network topology that reconnects all disconnected clients and ensures operation without technical problems, considering the forecasted load and generation for a given slot. For that, the process illustrated in Fig. 2 follows the steps:

- Evaluation of the critical period of each slot. The logic is that if a topology works during the critical period, it is highly likely to remain operable throughout the slot.
- Once a topology successfully reconnects all clients during the critical period, it is tested across the entire slot. If it performs successfully for the entire slot, the

solution is accepted, and the process ends, unless it is instructed to continue searching for alternatives.

- When evaluating a new slot, it is verified if this critical period has already been evaluated (e.g., due to overlapping slots, as in Fig.1). If so, the module reuses the existing results, avoiding redundant evaluations.

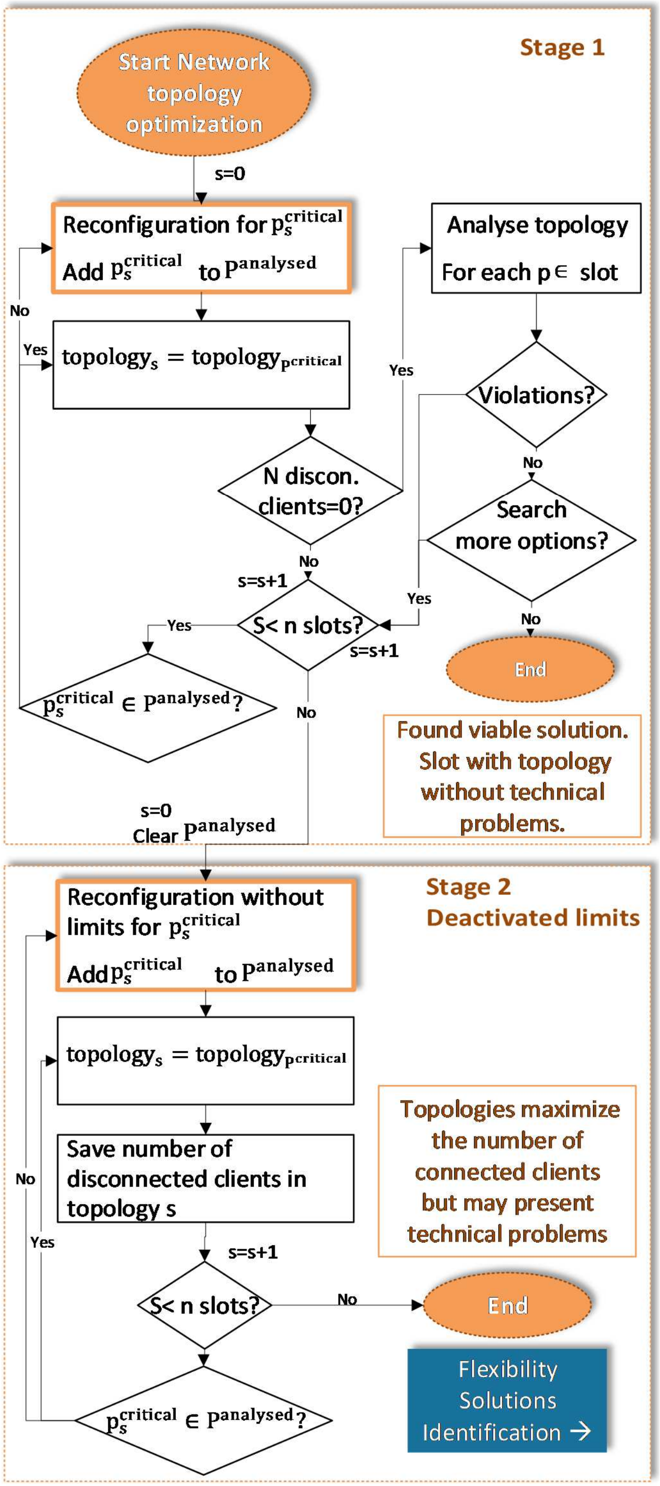

Figure 2. Network topology optimization module.

If Stage 1 identifies one or more viable solutions, maintenance activities are scheduled for the selected slot (or one of the available slots if multiple solutions exist), with the network reconfigured according to the determined optimal topology, and the tool completes its process. Otherwise, the process advances to Stage 2.

### *2) Stage 2:*

In this stage, a topology is defined for each suitable slot, aiming to feed the maximum number of clients, even if technical issues arise. For that, the technical limits are deactivated, specifically overloads and voltage limits, to prioritize reconnecting clients.

As in Stage 1, the critical period for each slot is evaluated. If the critical period has already been assessed the existing results are reused.

These topologies, which may exhibit technical problems, are passed to the next module - Flexibility Solution Identification - to determine the necessary flexibility to avoid these anticipated technical issues.

### *3) Reconfiguration process*

The reconfiguration process is responsible for defining the alternative network topology, and it is fully explained in the [10]. It begins with a network mapping process, where the topology is analyzed, and existing loops are identified and stored in a matrix. The EPSO particles' parameters represent the selected positions for opening each loop, determining the reconfigured topology.

In the fitness evaluation process, three steps are required: First, it assesses the network topology defined by the particle's parameters, verifying if there are closed loops. If so, these lines must be reverted to their initial positions. The second step includes evaluating the number of connected clients. If it is lower than past solutions, this solution is rejected. Then, a PF analysis is performed providing the necessary data to calculate the fitness function of current solutions. The fitness function minimized during topology reconfiguration in stage 1 is given by (1).

$$\min fit = \text{NetLosses} + \sum_{l}^{n\ lines} overl_l * \text{Penalty}_1 + \sum_{b}^{n\ busses} (voltage_b^{viol}) * \text{Penalty}_2 \qquad (1)$$

Where NetLosses represents the network losses for the current topology, $overl_l$ and $voltage_b^{viol}$ represent the branch overloads and voltage deviations beyond the allowable limits, which are multiplied by a Penalty.

In Stage 2, since the evaluation of technical limits is deactivated, the fitness function considers only network losses for the current topology.

## *E. Flexibility solution identification*

This module addresses technical issues anticipated in each slot operating under the predefined alternative topology, leveraging flexibility markets. As shown in Fig. 3, it interacts with the NODES market platform, which includes LongFlex (for reservations up to three weeks in advance) and ShortFlex (for activation in the day before).

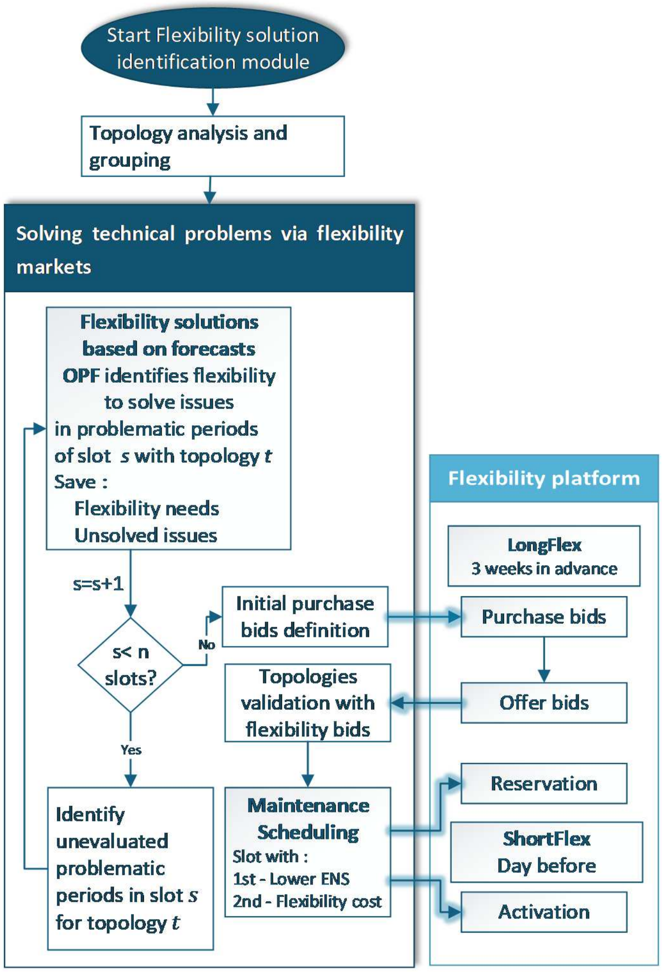

Figure 3. Flexibility solution identification module.

*1) Topology analysis and grouping process:*

This process analyzes the topologies generated for each slot to identify those with the same configurations. Slots sharing the same topology are grouped to eliminate redundant analysis of overlapping periods. Once grouped, it evaluates the periods within the slots for which this topology was designed, and it identifies the periods with technical issues, such as line overloads or voltage violations.

*2) Flexibility solutions:*

This process determines the flexibility requirements needed to solve technical issues in each problematic period. To achieve this, an Optimal Power Flow (OPF) analysis is conducted for the slot's topology. The OPF dispatches flexible resources to mitigate these issues.

As illustrated in Fig. 3, before analyzing a new slot, the process verifies whether the problematic periods for the given topology have already been evaluated. If they have, the previously obtained OPF results are reused.

*3) Initial Purchase bids definition*

This process initiates interaction with the market platform. Procurement bids must be submitted to the LongFlex market to receive responses (offer bids) detailing available flexibility levels and associated costs.

Before submission to the market, flexibility needs for each period are gathered and analyzed. As shown in Fig. 1, some periods may appear in multiple slots which may present different topologies, leading to varying flexibility requirements for the same period. In such cases, the highest flexibility value is selected and can later be adjusted in the "reservation" stage after choosing a slot for maintenance scheduling, as depicted in Fig. 3.

*4) Topologies validation with flexibility bids:*

After receiving the offer bids, each slot and its respective topology are analyzed using a simple power flow analysis, and the slots without technical issues are listed. If flexibility does not solve the technical issues for at least one slot, the slot with the lowest level of technical violations is selected. For this slot, a reconfigured topology is defined, as explained in D.3), to disconnect the minimum number of clients necessary to avoid the foreseen technical issues. This slot is then chosen to perform the maintenance activities.

At this stage, disconnected clients can result from the network's inability to reconnect those clients' area due to isolation or the lack of flexibility solutions to mitigate the technical issues associated with their reconnection.

Once the number of disconnected clients for each slot is calculated, the ENS for each slot can be easily calculated, as in (2). The flexibility cost for each slot is calculated using (4).

$$ENS_s = \sum_p^{p\ in\ s} ENS_p, \tag{2}$$

With,

$$ENS_p = \sum_c^{c\ in\ discon.client} abs(E_{c,p}). \tag{3}$$

$$Flex_s^{cost} = \sum_p^{p\ in\ s} Price_p * flex_p^{cap} \tag{4}$$

Where $E_{c,p}$ represents the energy consumed or produced by client $c$ on period $p$ (MWh), $Flex_s^{cost}$ denotes the flexibility cost for the slot $s$ (€), $Price_p$ is the flexibility price for period $p$ (€/MWh), and $flex_p^{cap}$ is the flexibility capacity contracted in period $p$ (MWh).

*5) Maintenance Scheduling*

In this process, the solutions are summarized and presented. The current topologies do not present technical problems, as these were solved either through the flexibility market or by disconnecting clients. This process suggests the maintenance schedule according to the following criteria:

- Slot with the lowest level of ENS.
- Slot with the lowest flexibility cost, in case of multiple solutions with the same ENS.

All solutions are presented, allowing the user to choose the option that best meets their objectives, such as limiting flexibility costs.

Once a slot is chosen, the flexibility reservation must be submitted to the LongFlex Market at least three weeks before maintenance date. The day before the scheduled maintenance, these bids must be activated in the ShortFlex Market, as shown in Fig. 3.

## III. CASE STUDY

This case study examines a 15 kV semi-urban Portuguese network with 578 connection points, including secondary substations and MV clients, from which 19 are PV producers.

Hourly forecasting profiles are considered for energy consumption and generation. Within this network, four clients provide flexibility services, with 15% consumption and 30% production reductions assumed as available flexibility.

These maintenance activities must be scheduled between Wednesday and Friday of a specific week, during daylight hours, from 9:00 to 18:00, to ensure adequate visibility. This maintenance work has an estimated duration of five hours.

## *IV. RESULTS AND DISCUSSION*

### *A. Slots definition*

The methodology begins by identifying all suitable time slots for maintenance. Based on the defined constraints, 15 slots were identified, each starting at/after 9:00 AM, lasting five hours, and ending no later than 6:00 PM over three specific days. Table III in the appendix presents these slots and highlights the respective critical period, representing the period with the highest ENS due to the isolation of maintenance area, which in this case resulted in the disconnection of 326 clients.

### *B. Network topology optimization*

This module searches for a topology that reconnects the 326 clients:

- From Stage 1, two different topologies were identified. However, neither was able to reconnect all clients without violating technical constraints. Only 25 of the initial 326 disconnected clients were successfully reconnected.
- In stage 2, the reconfiguration process allows technical limit violations, which will then be solved by contracting flexibility services. This stage generated two topologies able connect all the clients: one applicable to all time slots on day 1, and the other optimized based on profiles of days 2 and 3.

Table IV in the appendix presents the topologies from both stages, along with the number of disconnected clients and the corresponding time slots for which they were optimized.

### *C. Flexibility Solutions Identification*

In this module, the topologies derived from Stage 2 of the *network optimization* module are grouped to prevent redundant evaluations of same topologies during overlapping periods. Forecasts indicate that a specific line would be overloaded in both topologies, from 11:00 to 17:00 on days 1 and 3 and from 11:00 to 15:00 on day 2.

To address these anticipated violations, an OPF was conducted. The results determined that the flexibility services provided by a specific client, who is a producer, would be sufficient to avoid these issues. Table V in the appendix presents the flexibility needs for each period inside each slot, and Table I presents the flexibility bids that will be submitted to the market platform to avoid the identified issues.

The flexibility needs presented in Table I are submitted as purchase bids to the designated flexibility provider through the LongFlex market platform, which operates on a pay-as-bid basis. In this case, all the purchase bids were accepted and integrated into the selling bids. Since the flexibility capacity from purchasing and selling bids have the same values, Table II details only the costs of these identified flexibility services.

In this case study, the violations are fully resolved through flexibility services, allowing the new topologies to successfully reconnect all clients without any technical issues, resulting in zero ENS for all time slots. Table V in the appendix lists the flexibility needs in each period and flexibility costs for each slot, which are calculated using (4), considering the flexibility needs and the corresponding prices presented in Table II.

Slot 10 on Day 2, starting at 1:00 PM, presents the lowest cost. Although flexibility prices are higher on Day 2, the required flexibility capacity for this slot is significantly lower than in others.

In summary, since ENS is zero for all slots, the only selection criterion in this case is the flexibility cost. Therefore, Slot 10 is the recommended option along with the respective topology.

TABLE I. FLEXIBILITY NEEDS (MWH) - DECREASE INJECTION.

| **Flex. Needs** | **Time** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | ***10*** | ***11*** | ***12*** | ***13*** | ***14*** | ***15*** | ***16*** | ***17*** |
| Day 1 | 0 | 0.042 | 0.215 | 0.365 | 0.455 | 0.364 | 0.058 | 0 |
| Day 2 | 0 | 0.322 | 0.258 | 0.327 | 0.132 | 0 | 0 | 0 |
| Day 3 | 0 | 0.208 | 0.448 | 0.526 | 0.638 | 0.349 | 0.100 | 0 |

TABLE II. FLEXIBILITY COSTS (€/MWH) – SELLING BIDS.

| **Flex. Costs** | **Time** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | ***10*** | ***11*** | ***12*** | ***13*** | ***14*** | ***15*** | ***16*** | ***17*** |
| Day 1 | - | 1095 | 1095 | 1095 | 1095 | 1095 | 1095 | - |
| Day 2 | - | 1350 | 1350 | 1350 | 1350 | - | - | - |
| Day 3 | - | 1095 | 1095 | 1095 | 1095 | 1095 | 1095 | - |

## *V. CONCLUSION*

This paper presents a tool for scheduling planned maintenance activities in distribution networks, demonstrating how network reconfiguration, combined with flexibility services, can effectively maintain uninterrupted service during these activities. The tool starts by defining an alternative topology to operate the network during maintenance and identifies flexibility needs to prevent potential technical issues. Flexibility requests are then submitted to the market, and suitable bids are obtained to validate the network operation under the new topology and compare time slot options.

In the presented case study, the flexibility contracted through the market platform enabled the reconnection of 301 clients who would otherwise have been disconnected to accommodate maintenance actions within the desired time window. While flexibility costs could have reached €2376, the tool optimized the maintenance schedule, decreasing costs to €620, achieving a 74% reduction.

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## *APPENDIX*

TABLE III. SLOTS REPRESENTATION, INCLUDING THE CRITICAL PERIOD AND ENS BEFORE RECONFIGURATION.

| **ENS (MWh)** | **Day and Time** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | ***9*** | ***10*** | ***11*** | ***12*** | ***13*** | ***14*** | ***15*** | ***16*** | ***17*** |
| ***Day 1*** | | | | | | | | | |
| 1 | 3.10 | 3.81 | 4.25 | **4.43** | 4.03 | | | | |
| 2 | | 3.81 | 4.25 | **4.43** | 4.03 | 4.11 | | | |
| 3 | | | 4.25 | **4.43** | 4.03 | 4.11 | 4.08 | | |
| 4 | | | | **4.43** | 4.03 | 4.11 | 4.08 | 3.74 | |
| 5 | | | | | 4.03 | **4.11** | 4.08 | 3.74 | 3.12 |
| ***Day 2*** | | | | | | | | | |
| 6 | 2.65 | 3.62 | 3.78 | **4.14** | 3.68 | | | | |
| 7 | | 3.62 | 3.78 | **4.14** | 3.68 | 4.05 | | | |
| 8 | | | 3.78 | **4.14** | 3.68 | 4.05 | 3.99 | | |
| 9 | | | | **4.14** | 3.68 | 4.05 | 3.99 | 3.58 | |
| 10 | | | | | 3.68 | **4.05** | 3.99 | 3.58 | 3.12 |
| ***Day 3*** | | | | | | | | | |
| 11 | 2.86 | 3.68 | **4.14** | 4.03 | 4.01 | | | | |
| 12 | | 3.68 | 4.14 | 4.03 | 4.01 | **4.15** | | | |
| 13 | | | 4.14 | 4.03 | 4.01 | **4.15** | 4.07 | | |
| 14 | | | | 4.03 | 4.01 | **4.15** | 4.07 | 3.69 | |
| 15 | | | | | 4.01 | **4.15** | 4.07 | 3.69 | 3.17 |

TABLE IV. NETWORK TOPOLOGIES FOR STAGES 1 AND 2.

| | **Alternative topologies** | | | | |
|---|---|---|---|---|---|
| | ***1*** | ***2*** | ***3*** | ***4*** | ***Final state*** |
| Changed Switches | SW321 | SW321 | SW321 | SW321 | Open |
| | SW322 | SW322 | SW322 | SW322 | Open |
| | SW2DF | SW2DF | SW2DF | SW2DF | Closed |
| | SW008 | SW008 | SW024 | SW024 | Open |
| | SW024 | SW175 | SW031 | SW031 | Open |
| | SW175 | SW26D | SW045 | SW045 | Open |
| | SW21F | | SW175 | SW175 | Open |
| | SW29C | | SW29C | SW21F | Open |
| | | | SW327 | SW29C | Open |
| | | | | SW327 | Open |
| | SW026 | SW026 | SW026 | SW026 | Closed |
| | SW069 | SW0E5 | SW0B9 | SW069 | Closed |
| | SW0B9 | | SW0C8 | SW0B9 | Closed |
| | SW0E5 | | SW0E5 | SW0C8 | Closed |
| | | | SW1AE | SW0E5 | Closed |
| | | | SW1F6 | SW1AE | Closed |
| | | | | SW1F6 | Closed |
| Discon. Clients | 301 | 301 | 0 | 0 | |
| Viol. | 0 | 0 | 1 | 1 | |
| Slots | 1 2 3 4 5 | 6 7 8 9 10 11 12 13 14 15 | 1 2 3 4 5 | 6 7 8 9 10 11 12 13 14 15 | |

TABLE V. FLEXIBILITY NEEDS PER SLOT (DETAILED BY PERIOD) AND CORRESPONDING FLEXIBILITY COSTS

| **Flex. Needs (MWh)** | **Time** | | | | | | **Slot Flex. Costs (€)** |
|---|---|---|---|---|---|---|---|
| | ***11*** | ***12*** | ***13*** | ***14*** | ***15*** | ***16*** | |
| ***Day 1*** | | | | | | | |
| 1 | 0.042 | 0.215 | 0.365 | | | | 680.45 |
| 2 | 0.042 | 0.215 | 0.365 | 0.455 | | | 1178.39 |
| 3 | 0.042 | 0.215 | 0.365 | 0.455 | 0.364 | | 1577.01 |
| 4 | | 0.215 | 0.365 | 0.455 | 0.364 | 0.058 | 1594.25 |
| 5 | | | 0.365 | 0.455 | 0.364 | 0.058 | 1359.04 |
| ***Day 2*** | | | | | | | |
| 6 | 0.322 | 0.258 | 0.327 | | | | 1225.03 |
| 7 | 0.322 | 0.258 | 0.327 | 0.132 | | | 1403.76 |
| 8 | 0.322 | 0.258 | 0.327 | 0.132 | 0.000 | | 1403.75 |
| 9 | | 0.258 | 0.327 | 0.132 | 0.000 | 0.000 | 968.45 |
| 10 | | | 0.327 | 0.132 | 0.000 | 0.000 | 620.13 |
| ***Day 3*** | | | | | | | |
| 11 | 0.208 | 0.448 | 0.526 | | | | 1295.21 |
| 12 | 0.208 | 0.448 | 0.526 | 0.638 | | | 1993.47 |
| 13 | 0.208 | 0.448 | 0.526 | 0.638 | 0.349 | | 2375.94 |
| 14 | | 0.448 | 0.526 | 0.638 | 0.349 | 0.100 | 2257.96 |
| 15 | | | 0.526 | 0.638 | 0.349 | 0.100 | 1767.2 |