ATTEST

WP3

Optimal Planning Tools for Transmission and Distribution Systems

Optimization Tool for Planning TSO-DSO Shared Technologies

User Guide

D3.4

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Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

ACRONYM / ABBREVIATION	Extensive form
AC	ALTERNATING CURRENT
DER	DISTRIBUTED ENERGY RESOURCE
DR	DEMAND RESPONSE
DM	DATA MANAGER
DN	DISTRIBUTION NETWORK
DSO	DISTRIBUTION SYSTEM OPERATOR
ESS	ENERGY STORAGE SYSTEM
ESSO	ENERGY STORAGE SYSTEM OWNER
EV	ELECTRIC VEHICLE
NPV	NET PRESENT VALUE
OLTC	ON-LOAD TAP CHANGER
RES	RENEWABLE ENERGY SOURCES
ROI	RETURN ON INVESTMENT
SMOPF	STOCHASTIC MULTI-PERIOD OPTIMAL POWER FLOW
SoC	STATE-OF-CHARGE
TN	TRANSMISSION NETWORK
TSO	TRANSMISSION SYSTEM OPERATOR
WP	WORK PACKAGE

1. Executive summary

The electric power system is rapidly evolving to meet the target of net-zero emissions. This involves both energy transition to low-carbon and renewable energy sources, and increasing adoption of automation, digitalization, regulation, and data collection to enable flexibility services. This imposes great technical and economic challenges to the operation and planning of future energy systems. The ATTEST project aims to solve some of these challenges by developing an open-source toolbox comprising a suite of innovative tools to support TSO-DSO synergic operation, optimal asset management and coordinated planning of both transmission and distribution systems for 2030 and beyond.

This document presents deliverable D3.4, which provides a user guide for the tool developed within Task 3.3 of the ATTEST project (Optimization Tool for Planning TSO-DSO Shared Technologies) which includes detailed information about the types and formats of input and output data; computational requirements; and existing interactions with other tools. The document also provides some results for test case “HR1”, corresponding to Koprivnica region in Croatia, which is a test case that was shared in the project’s repository.

2. Introduction

Electric power systems are currently experiencing a profound change, as increasing amounts of Renewable Energy Sources (RESs) displace conventional forms of generation. This development has gone hand-in-hand with an expanding share of power production taking place at the distribution level, and the connection of new types of Distributed Energy Resources (DERs) – such as Energy Storage Systems (ESSs), Electric Vehicles (EVs), and active (flexible) consumers, who have started to actively participate in the market either by taking the role of producer-consumer ("prosumer") or by engaging in Demand Response (DR) programs. These trends are expected to continue and will require a profound revision of the way Transmission Systems Operators (TSOs) and Distribution System Operators (DSOs) interact with each other [1].

The objective of the ATTEST project is to develop a modular open-source toolbox comprising a suite of innovative tools to support TSO-DSO synergistic operation, optimal asset management, and coordinated planning of both transmission and distribution systems for 2030 and beyond, considering technical, economic, and environmental objectives. This deliverable provides details regarding the methodology, implementation, and usage of the tool developed within Task 3.3 -- Optimization Tool for Planning TSO/DSO Shared Technologies.

2.1. Optimal Design and Planning Tools for Transmission and Distribution Systems

The aim of WP3 in the ATTEST project is to develop new planning tools for electrical distribution and Transmission Networks (TNs) that support (and benefit from) emerging TSO-DSO markets and technologies. The planning tools model the flexibility which is aggregated from smart multi-energy customers to trade services, including network support, in the different markets. Unlike traditional congestion-driven network reinforcements, ATTEST framework for planning also considers the use of demand-side flexibility for new business cases to extract the maximum value from the trade of flexibility through the TSO-DSO interface.

2.2. Optimization Tool for Planning TSO-DSO Shared Technologies

In Task 3.3, a planning tool for TSO-DSO shared technologies was developed. The tool is focused on the planning of shared ESSs that can simultaneously be used by TSO and DSOs. It is considered that the investment in the shared ESSs is performed by a third-party investor, the Energy Storage System Owner (ESSO), that can participate in energy and secondary reserve markets. The outcome of the tool is an adaptive investment plan in shared ESSs to be installed at the boundary nodes (primary substations) between the transmission and distribution networks participating in the coordination scheme. In the scope of the ATTEST project, a new TSO-DSO coordination mechanism was proposed, with the objective of exploiting the growing flexibility at the Distribution Network (DN) level with the overall power system. Further details regarding ATTEST's TSO-DSO coordination mechanism are provided in D2.4 [2]. This coordination mechanism was extended in Task 3.3, to consider the existence of TSO-DSO shared technologies. Further details regarding the proposed coordination mechanism in the presence of shared resources is provided in subsection "3.3 -- TSO-DSO Coordination Mechanism in the Presence of Shared ESSs".

2.3. Structure of the Report

The rest of the document is structured as follows:

- Section 3 provides a functional description of the proposed optimization tool for planning of TSO-DSO shared technologies
- Section 4 provides a user guide on how to execute the tool, and describes input and output data and their structure
- Section 5 presents the results for an example test case
- Section 6 concludes the deliverable.

3. Optimization Tool for Planning TSO-DSO Shared Technologies

Traditionally, transmission and distribution systems have been independently managed by TSO and DSOs, respectively, based on oversimplified models regarding each other's network [3]. Demand has been supplied by large-scale generating units connected to the transmission level, thereby allowing distribution systems to be passively operated, based on a "fit-and-forget" approach. However, coordination and active interactions between the transmission and DNs is required to take advantage of the potential benefits that the increasing volumes of DERs can bring to the operation of the overall electric power system [4]. It is expected that the exploitation of these resources will facilitate the increasing penetration of RES at a lower cost for consumers by (i) reducing the need to procure services from conventional generation, (ii) reducing investment costs, and (iii) improving asset utilization [5] [6].

For high levels of renewable energy and active consumer participation in power system operation, the balancing task becomes more complicated. Effectively dealing with the uncertainty derived from these types of resources requires more flexibility [7]. Energy storage increases the flexibility of power systems and therefore their ability to deal with uncertainty is recognized as a valuable means to provide additional system security, reliability and capacity to respond to changes that are difficult to accurately forecast [8]. The increasing uncertainty associated with network operation creates new opportunities for ESS integration at different levels of the electric power system [9]. However, although ESS technology is maturing and continuously reducing in cost, these still require a relatively high initial investment. Due to unbundling regulation, it is likely that many of these ESSs will be deployed by private investors, and therefore we should consider not only whether they can provide social benefits in terms of reduced operational costs, but also whether they generate sufficient Return On Investment (ROI) [10]. To reduce the risk of stranded assets, these investments should be robust with respect to errors in the long-term evolution of the load and renewable generation capacity [11].

As it was reported in D3.1 [12], a lot of work has been published in the ESS planning field. However, so far, most of the published work is mainly focused on the optimal investment in ESS either from an independent investor, DSO, or TSO perspective. Furthermore, only recently the models adopted for ESS planning have started to consider more complex topics, such as energy capacity degradation, the full Alternating Current (AC) formulation of the power flow equations, and uncertainty associated with the operation of the network. It was also shown that the topic of TSO-DSO coordination is still in its infancy, and little to no research has been published on the joint-planning of ESSs or planning of ESSs in the presence of these types of coordination schemes.

In Task 3.3, a planning tool for TSO-DSO shared technologies is proposed. The tool considers that the TSO and DSOs coordinate their operation according to the TSO-DSO coordination mechanism proposed in D2.4 of the ATTEST project [2]. This coordination mechanism was extended in Task 3.3, to consider the presence of shared technologies, that can simultaneously be used by TSO and DSOs. Further details regarding the extended TSO-DSO coordination mechanism are provided below, in subsection 3.3.

3.1. Functional Description

The tool developed within Task 3.3 has several innovations relatively to the current state-of-the-art. To the best of our knowledge, it is the first time that a planning tool for TSO-DSO shared resources is being proposed under a TSO-DSO coordination mechanism, from the perspective of a third-party investor.

As it was previously described, it is considered that the investment in the shared ESSs is performed by a third-party entity, the ESSO, which can participate in the energy and secondary reserve markets. Besides the TSO-DSO coordination mechanism, the tool considers several other key aspects: (i) an adaptive investment plan, i.e., it is considered that the power and energy capacities of the shared ESSs can be upgraded over the planning period; (ii) capacity degradation of the battery ESSs; (iii) a full AC formulation of the networks' power flow equations; (iv) flexibility from asset and non-asset-based solutions; and (v) uncertainties related to the operation of the networks, shared ESSs, and market prices. Furthermore, the data privacy of the several agents involved in the optimization problem is preserved, through mathematical decomposition techniques.

The tool receives as inputs the optimal reinforcement plans in DNs and TN (from Task 3.1 and Task 3.2, respectively), market prices (energy, reserve, flexibility) and operational forecasts (RES generation, load, flexibility). The outcome of the tool is an investment plan in shared ESSs to be installed at the boundary points between the transmission and distribution networks participating in the coordination scheme. This investment plan is adaptive, in the sense that the ESSs' capacity can be upgraded over the planning horizon. It is considered that the degradation of the battery ESSs derive from calendric ageing (i.e., ageing related to the ESS components' calendar life) and cyclic ageing (related to charging and discharging cycles of the ESS). The tool accounts for two main types of uncertainty, operational uncertainties and market uncertainties. Network operational uncertainties are associated to forecasts of renewable generation and load. Shared ESS operational uncertainties are associated with the forecasts of secondary reserve requirements. Market price uncertainties are associated with the forecasts of energy and reserve market prices. Furthermore, asset and non-asset-based flexibility solutions are considered. Asset-based resources include transformers equipped with On-Load Tap Changers (OLTC) and ESSs. Non-asset-based solutions include consumers participating in DR programs.

The tool recurs to distributed optimisation methods with two main objectives: to preserve the tractability of this large-scale optimization problem; and to preserve the data privacy of the several agents involved in the optimization process.

3.2. Proposed Framework

The proposed framework consists of a bi-level optimization problem. Figure 1 shows an illustrative diagram of the bi-level planning tool. The upper-level problem of the planning tool determines investment decisions, i.e., power and energy capacity to be installed per year at each interface node with DNs that participate in the TSO-DSO coordination mechanism. At the lower-level, the coordinated operational planning between TSO and DSOs is simulated considering the TSO-DSO coordination mechanism selected in the ATTEST project to determine the operational planning revenue of the ESSO.

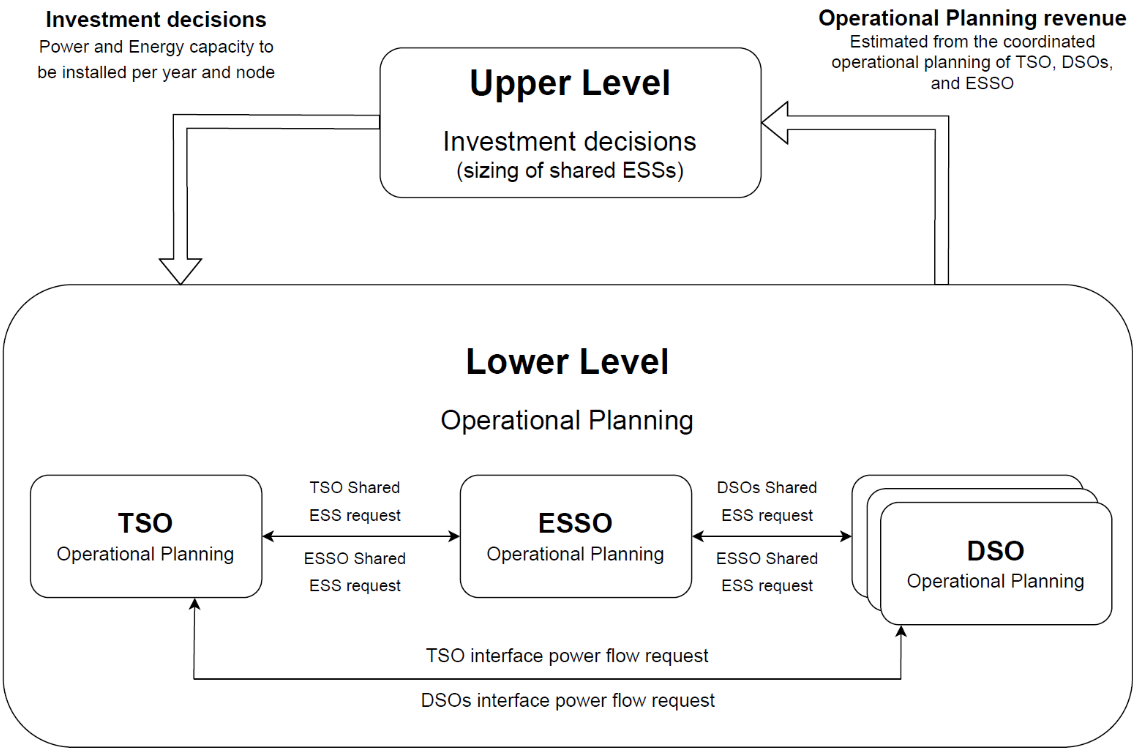


FIGURE 1 – SHARED RESOURCES PLANNING. ILLUSTRATIVE HIGH-LEVEL DIAGRAM OF THE PROPOSED FRAMEWORK.

This bi-level problem is solved through a Benders' decomposition method [13]. Benders' decomposition is an iterative method, where a master (or upper-level) problem, and a subproblem (lower-level), or set of subproblems, are solved alternatively, in an iterative fashion. At the upper-level, the values for the complicating (or coupling) variables are determined and are then communicated to the lower-level. The value of the upper-level's problem objective function is the lower bound of the overall problem. The lower-level problem(s) is then solved, assuming that the values of the complicating variables are fixed. Then, the lower-level communicates the value of objective function (upper bound of the overall problem), and the value of the sensitivities (dual variables) of the complicating variables to the upper-level problem. With the upper bound and sensitivity values, a restriction is added to the upper-level problem (the so-called Benders' cut), that narrows the feasible solution space, and the problem is solved again. Then, new values of the complicating variables are determined and communicated once again to the lower-level problem. Convergence and final results are reached when the lower and upper bounds of the overall problem converge to an admissible tolerance.

In the case of the TSO-DSO shared resource planning tool proposed, it is assumed that the complicating variables are the values of power and energy capacity of the ESS to be installed at each interface node and each year of the planning horizon. The lower bound of the problem is the total profit obtained by the ESSO for the planning horizon, in Net Present Value (NPV). The upper bound of the problem is the operational planning revenue obtained by the ESSO, also in NPV.

3.3. TSO-DSO Coordination Mechanism in the Presence of Shared ESSs

As it was described in D2.4, the TSO-DSO coordination scheme proposed in ATTEST consists of a 5-step procedure, where active and reactive bids are decoupled. Succinctly, ATTEST's coordination mechanism consists of the following steps [2]:

1. The DER present in the DN submit their bids to the DSO
2. The DSO determines the active power flexibility band that it can provide to the TSO at the transmission-distribution interface, considering the available DER flexibility
3. The TSO, considering this active power flexibility band, optimizes its own network and communicates the desired active power flow profile to the DSO
4. The DSO, knowing the desired active power flow profile, determines the reactive power flexibility band that it can provide to the TSO at the transmission-distribution interface
5. The TSO, considering this reactive power flexibility band, optimizes its own network and communicated the desired reactive power flow profile to the DSO

To mathematically formulate the TSO-DSO coordination mechanism in the presence of shared ESSs, while preserving the data privacy of the different agents involved in the optimization process, the proposed TSO-DSO coordination mechanism was upgraded and implemented using the Alternating Direction Method of Multipliers (ADMM) algorithm [14]. The motivation for this modification of the TSO-DSO coordination mechanism is related to the fact that the proposed methodology does not consider the existence of shared resources, that can be simultaneously used by TSO and DSOs. Figure 2 shows a diagram of the proposed TSO-DSO coordination mechanism that was implemented in the TSO-DSO shared technologies planning tool.

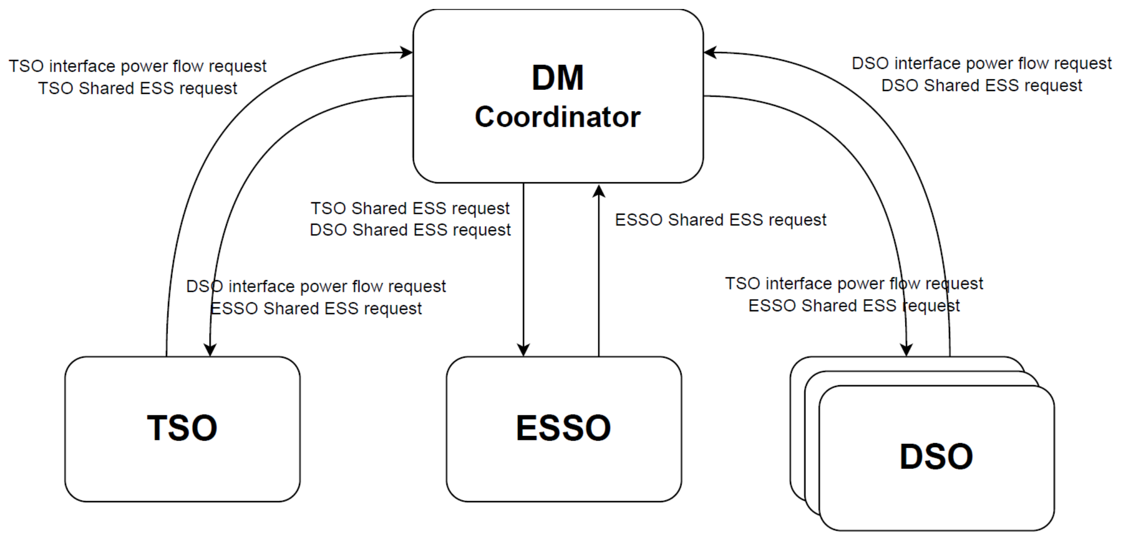


FIGURE 2 – SHARED RESOURCES PLANNING. OPERATIONAL PLANNING. ILLUSTRATIVE DIAGRAM OF THE PROPOSED TSO-DSO-ESSO COORDINATION MECHANISM.

Essentially, in the proposed method, the lower-level (operational planning) problem is decomposed by the several actors that participate in the coordination mechanism, in this case the TSO, DSOs, and the ESSO. By decomposing the operational planning problem in TSO, DSOs, and ESSO subproblems, we must ensure that all these agents reach a consensus regarding the coupling variables of the operational planning problem – active and reactive power flows at the TSO-DSO interface, and power profiles of the shared ESSs.

The coordination mechanism in the presence of shared resources can be summarized as:

1. ESSO Optimization:
    1.1. The ESSO runs its optimization problem, that has the objective of maximizing its operational revenue when participating in the energy and secondary reserve markets, and determines the shared ESSs' power profiles
    1.2. The desired shared ESSs power profiles are then communicated to an independent central entity, the network Data Manager (DM), responsible for handling the data communications between the several actors. The DM then communicates the shared ESSs power profiles desired by the ESSO to the TSO and DSOs participating in the coordination mechanism
2. DSOs Optimization:
    2.1. The DSOs run a Stochastic Multi-Period Optimal Power Flow (SMOPF) with the objective of minimizing network technical violations, while considering the existence of the shared ESS at the interface with the TN and the available DER. This formulation respects the previously defined coordination scheme, since the DSO's only objective is to minimize network technical violations (and therefore safely provide the flexibility available at the distribution level to the transmission level), and correspond to the TSO's requests
    2.2. The results of this optimization process, i.e., the desired active and reactive power profiles at the TSO-DSO interface and the shared ESS power profile desired by the DSOs are then communicated to the DM, which forwards them to TSO and ESSO, respectively
3. TSO Optimization:
    3.1. The TSO runs its own operational planning problem (i.e., a SMOPF), with the objective of minimizing operational cost, considering the active and reactive power flows desired by the DSOs at the TSO-DSO interface, and shared ESS power profile desired by the ESSO, and determines the new (desired) active and reactive power profiles at the TSO-DSO interface and shared ESS power profile
    3.2. The new interface power flows and shared ESS power profiles are once again communicated to the network DM that forwards those requests to the adequate agents (DSOs, ESSO).

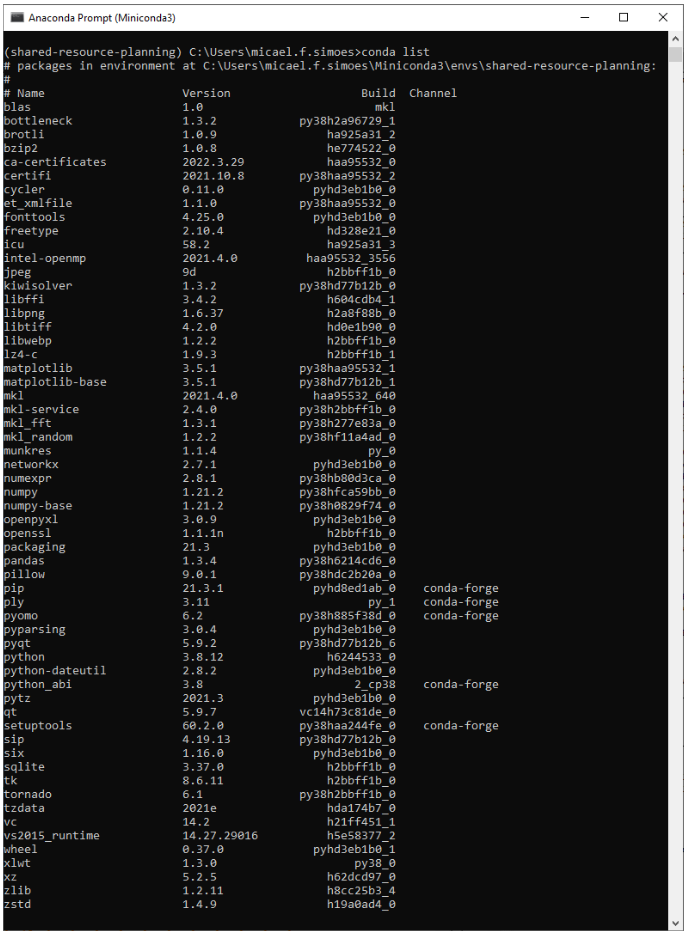
The iterative process continues, until a consensus regarding the active and reactive power flow profiles at the TSO-DSO interface and shared ESS power profile is achieved. It is important to note that with this coordination scheme, the philosophy behind the initially proposed coordination scheme is still valid, i.e., that the flexibility existing at the DN level can be shared with the overall power system in a safe manner.

4. User Guide

The optimization tool for planning of TSO-DSO shared technologies was implemented in the Python programming language [15], recurring to the Pyomo optimization modelling language [16], [17]. Pyomo is an open-source library that allows the modelling of the optimization problem without being tied to a specified solver framework (such as CPLEX [18] or Gurobi [19] optimization frameworks for Python). Therefore, it supplies a level of abstraction between the problem's modelling and solving procedures, allowing the user to test different optimizers and select the optimizer that is most adequate to solve its problem. In the following subsections we describe the tool's requirements, how to run it from a command line interface, and input and output data formats.

4.1. Requirements

It is recommended the usage of a conda environment [20], to avoid conflicts between different versions of libraries and tools used or installed in the same computer. In Figure 3, it is shown a screenshot of the packages installed in the environment used to develop the shared ESS planning tool. A yaml [21] file will be shared in the project repository, to help the user create a similar conda environment.



```
Anaconda Prompt (Miniconda3)

(shared-resource-planning) C:\Users\micael.f.simoes>conda list
# packages in environment at C:\Users\micael.f.simoes\Miniconda3\envs\shared-resource-planning:
#
# Name                    Version                   Build  Channel
blas                      1.0                         mkl
bottleneck                1.3.2            py38h2a96729_1
brotli                    1.0.9                ha925a31_2
bzip2                     1.0.8                he774522_0
ca-certificates           2022.3.29            haa95532_0
certifi                   2021.10.8        py38haa95532_2
cycler                    0.11.0             pyhd3eb1b0_0
et_xmlfile                1.1.0            py38haa95532_0
fonttools                 4.25.0             pyhd3eb1b0_0
freetype                  2.10.4               hd328e21_0
icu                       58.2                 ha925a31_3
intel-openmp              2021.4.0          haa95532_3556
jpeg                      9d                   h2bbff1b_0
kiwisolver                1.3.2            py38hd77b12b_0
libffi                    3.4.2                h604cdb4_1
libpng                    1.6.37               h2a8f88b_0
libtiff                   4.2.0                hd0e1b90_0
libwebp                   1.2.2                h2bbff1b_0
lz4-c                     1.9.3                h2bbff1b_1
matplotlib                3.5.1            py38haa95532_1
matplotlib-base           3.5.1            py38hd77b12b_1
mkl                       2021.4.0           haa95532_640
mkl-service               2.4.0            py38h2bbff1b_0
mkl_fft                   1.3.1            py38h277e83a_0
mkl_random                1.2.2            py38hf11a4ad_0
munkres                   1.1.4                      py_0
networkx                  2.7.1              pyhd3eb1b0_0
numexpr                   2.8.1            py38hb80d3ca_0
numpy                     1.21.2           py38hfca59bb_0
numpy-base                1.21.2           py38h0829f74_0
openpyxl                  3.0.9              pyhd3eb1b0_0
openssl                   1.1.1n               h2bbff1b_0
packaging                 21.3               pyhd3eb1b0_0
pandas                    1.3.4            py38h6214cd6_0
pillow                    9.0.1            py38hdc2b20a_0
pip                       21.3.1             pyhd8ed1ab_0    conda-forge
ply                       3.11                       py_1    conda-forge
pyomo                     6.2              py38h885f38d_0    conda-forge
pyparsing                 3.0.4              pyhd3eb1b0_0
pyqt                      5.9.2            py38hd77b12b_6
python                    3.8.12               h6244533_0
python-dateutil           2.8.2              pyhd3eb1b0_0
python_abi                3.8                      2_cp38    conda-forge
pytz                      2021.3             pyhd3eb1b0_0
qt                        5.9.7            vc14h73c81de_0
setuptools                60.2.0           py38haa244fe_0    conda-forge
sip                       4.19.13          py38hd77b12b_0
six                       1.16.0             pyhd3eb1b0_0
sqlite                    3.37.0               h2bbff1b_0
tk                        8.6.11               h2bbff1b_0
tornado                   6.1              py38h2bbff1b_0
tzdata                    2021e                hda174b7_0
vc                        14.2                 h21ff451_1
vs2015_runtime            14.27.29016          h5e58377_2
wheel                     0.37.0             pyhd3eb1b0_1
xlwt                      1.3.0                   py38_0
xz                        5.2.5                h62dcd97_0
zlib                      1.2.11               h8cc25b3_4
zstd                      1.4.9                h19a0ad4_0
```

FIGURE 3 – SHARED RESOURCES PLANNING TOOL EXECUTION. EXAMPLE OF CONDA ENVIRONMENT. INSTALLED PACKAGES.

4.2. Tool Execution

The tool can be executed from a command line prompt by running the command "python main.py [OPTIONS]". The conda environment where the required packages are installed should be activated when the tool is executed. Instructions regarding the tool execution are given if the arguments are incorrect or insufficient, or if the help command ("-h" or "—help") is typed. Figure 4 shows the command line interface for the execution of shared resources planning tool.

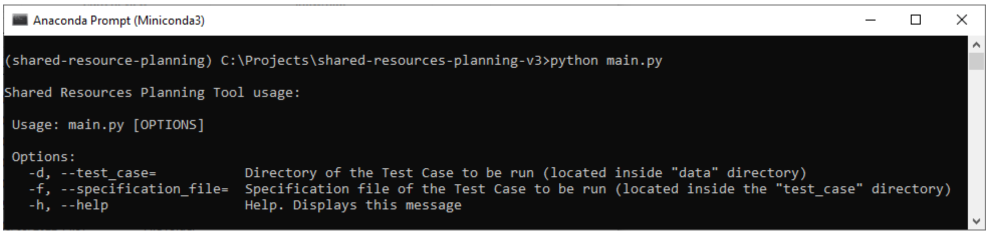


FIGURE 4 - SHARED RESOURCES PLANNING TOOL EXECUTION. COMMAND LINE INTERFACE.

The tool expects to receive two arguments, "test_case", which corresponds to the test case to be run, and "specification_file" that corresponds to the file where the test case execution data (configuration parameters) is specified. Further details regarding the structure of the test cases and specification file are given in the next subsections.

4.3. Test Case -- Directory Structure

It is assumed that the test case's input data is located in a subdirectory with the name in the directory "data". In the future, the tool will be integrated in the project's toolbox, and this data will be available directly in a database. Figure 5 shows the directory structure of the example test case "HR1", which corresponds to part of the Croatian network in the Koprivnica region.

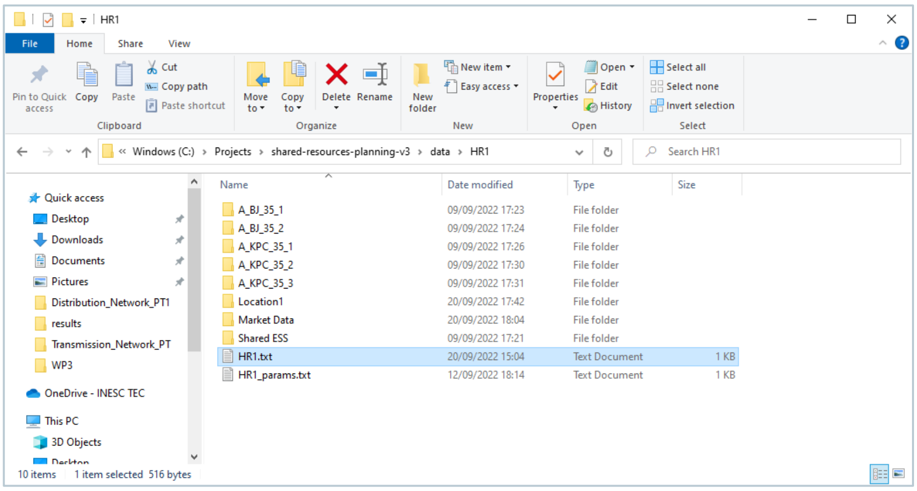


FIGURE 5 – SHARED RESOURCES PLANNING. TEST CASE DEFINITION. DIRECTORY STRUCTURE OF THE PLANNING TEST CASE.

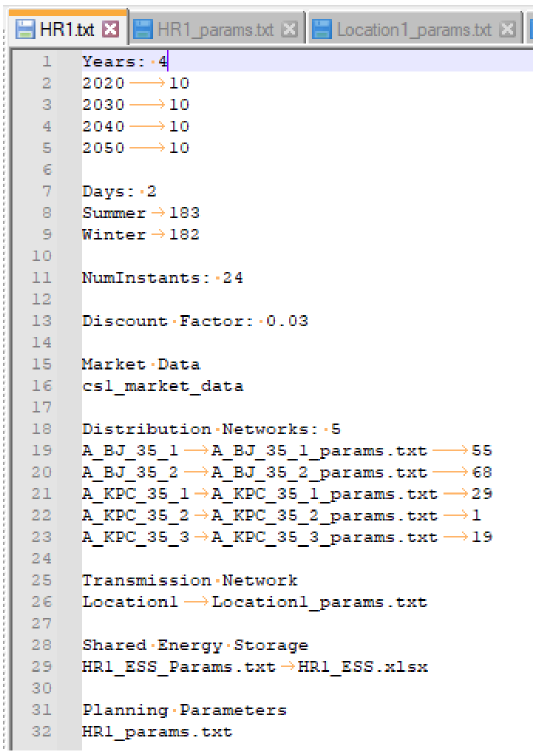
Due to the large amount of input data, the data was organized in several directories corresponding to the different parties or types of data involved in the planning procedure. The test case directory should contain:

- One directory per DN considered in the planning problem. In the example in Figure 5, there are 5 DNs, namely "A_BJ_35_1", "A_BJ_35_2", "A_KPC_35_1", "A_KPC_35_2", and "A_KPC_35_3")
- One directory for the TN ("Location1" in the example of Figure 5)
- One directory containing the market data ("Market Data"); and
- One directory containing the shared ESS data ("Shared ESS").

Additionally, the test case directory should contain a *Specification* file (in the example of Figure 5, "HR1.txt"), the main file where the problem is defined, and a *Planning Parameters* file ("HR1_params.txt" in Figure 5), that contains information regarding the planning parameters of the problem, respectively.

4.4. Specification file

The *Specification* file corresponds to the main specification file of the test case, where the general information of the planning problem is defined, i.e., TN and DNs to be considered and corresponding *Network Parameters* files, representative years and days, discount factor, shared ESS data files, and *Planning Parameters* files. Figure 6 shows an example of a *Specification* file.




```
Years: 4
2020	10
2030	10
2040	10
2050	10

Days: 2
Summer	183
Winter	182

NumInstants: 24

Discount Factor: 0.03

Market Data
csl_market_data

Distribution Networks: 5
A_BJ_35_1	A_BJ_35_1_params.txt	55
A_BJ_35_2	A_BJ_35_2_params.txt	68
A_KPC_35_1	A_KPC_35_1_params.txt	29
A_KPC_35_2	A_KPC_35_2_params.txt	1
A_KPC_35_3	A_KPC_35_3_params.txt	19

Transmission Network
Location1	Location1_params.txt

Shared Energy Storage
HR1_ESS_Params.txt	HR1_ESS.xlsx

Planning Parameters
HR1_params.txt
```

FIGURE 6 - SHARED RESOURCES PLANNING TEST CASE DEFINITION. *SPECIFICATION* FILE.

The *Specification* file is organized in the following sections:

- The first section corresponds to the representative years. In the above example of Figure 6, the tool will be run considering current conditions (2020) and a planning horizon of 40 years with 10 years steps, i.e., 2020, 2030, 2040 and 2050
- The second section corresponds to the number of representative days to be simulated per year. In this case, two representative days are considered, “Summer” and “Winter” totaling 183 and 182 days, respectively
- The third section corresponds to the number of time steps to be considered per day, in this case, 24 time steps (i.e., NumInstants: 24)
- The fourth section corresponds to the discount factor (average interest rate) to be used in the NPV calculation, in this case 3%
- The fifth section corresponds to the prefix of the market data files. In this case, the program will search for 4 files located in the “Market Data” directory, “cs1_market_data_2020.xlsx”, “cs1_market_data_2030.xlsx”, etc., corresponding to the 4 representative years of simulation
- The sixth section corresponds to the DNs considered in the planning procedure. In this case, a total of 5 DNs are participating in the TSO-DSO coordination scheme (“A_BJ_35_1”, “A_BJ_35_2”, “A_KPC_35_1”, “A_KPC_35_2”, and “A_KPC_35_3”). The first field corresponds to the name (or designation) of the network; the second field corresponds to the file where the *Network Parameters* are specified (further details provided in subsection 4.6.2.2); and the third field is the connection node ID of the TN
- The seventh section corresponds to the TN definition. The first field corresponds to the name of the network; and the second field corresponds to the *Network Parameters* file
- The eighth section corresponds to the shared ESSs data. The first field corresponds to the *Shared ESS Parameters* file; the second field corresponds to the excel file that contains the operational data corresponding to the shared ESSs
- Finally, the ninth section corresponds to the *Planning Parameters*. In this example, file “HR1_params.txt” contains the data related to the decomposition methodologies employed to the shared ESSs planning problem.

In the following subsections the information and format that each of these files and directories should contain is specified.

4.5. Planning Parameters file

The *Planning Parameters* file contains information regarding the decomposition techniques used to solve the TSO-DSO shared resources planning problem. Figure 7 shows an example of a *Planning Parameters* file.

HR1_params.txt | HR1_ESS_params.txt

```
Benders
benders_tol_abs = 1e3
benders_tol_rel = 0.001e-2
benders_num_max_iters = 1000

ADMM
admm_tol = 1e-3
admm_num_max_iters = 100
rho
Location1 = 0.50
A_BJ_35_1 = 0.50
A_BJ_35_2 = 0.50
A_KPC_35_1 = 0.50
A_KPC_35_2 = 0.50
A_KPC_35_3 = 0.50
ESSO = 1.00
```

FIGURE 7 – SHARED RESOURCES PLANNING. TEST CASE DEFINITION. *PLANNING PARAMETERS* FILE.

The *Planning Parameters* file has the following sections:

- The first section contains information regarding the Benders' decomposition parameters used by the model. *benders_tol_abs* and *benders_tol_rel* correspond to the absolute tolerance and relative tolerance, to be considered in the convergence criteria definition, respectively; and *benders_num_max_iters* is the maximum number of iterations to be considered. In the example of Figure 7, it is considered that the optimization problem converges when the difference between the upper and lower bound is inferior to 1000 m.u., or when the relative difference is inferior to 0.001%. The maximum number of iterations is 1000.
- The second section contains the selected setting for the ADMM decomposition parameters. *admm_tol* is the tolerance to be considered in the convergence criteria definition; and *admm_num_max_iters* is the maximum number of iterations. Next, there is a subsection where the ρ (ADMM parameter) of each agent participating in the coordination planning problem is defined. It should exist one ρ for the TN, one ρ per DN, and one ρ for the ESSO. In the example of Figure 7, it is considered that the TN ("Location1") and DNs ("A_BJ_35_1", "A_BJ_35_2", "A_KPC_35_1", "A_KPC_35_2", and "A_KPC_35_3") have a ρ of 0.50, and ESSO has a ρ of 1.00.

4.6. Input Data

4.6.1. *Shared ESS* Information

The input data related to the shared ESS should be placed in the directory "Shared ESS". The shared ESS information consists of two files, one related to the *Shared ESS Parameters*, and one related to *Shared ESS Data*. It is assumed that all shared ESSs have a calendar life of 20 years, a nominal cycle life of 3650 cycles, and a nominal depth-of-discharge of 80%.

4.6.1.1. Shared ESS Parameters file

The *Shared ESS Parameters* file contains information to be considered in the shared ESS optimization problem, solver parameters, and information related to the tool's outputs. Figure 8 shows an example of a *Shared ESS Parameters* file.

```
budget = 1e6
max_capacity = 2.50
min_pe_factor = 0.10
max_pe_factor = 4.00
plot_results = False
print_results_to_file = True
solver = "ipopt"
linear_solver = "ma57"
solver_path = "C:\Lib\optim\dist\bin\ipopt.exe"
solver_tol = 1e-6
verbose = False
```

FIGURE 8 - SHARED RESOURCES PLANNING. SHARED ESS TEST CASE DEFINITION. *SHARED ESS PARAMETERS* FILE.

The *Shared ESS Parameters* file contains the following information regarding investment constraints:

- *budget*: Investment budget of the ESSO. In the example of Figure 8 it is considered that the ESSO has an investment budget of 1Mm.u., in NPV
- *max_capacity*: Maximum energy capacity, in MVAh, that can be installed per node (i.e., shared ESS). This constraint is related to the space available at the primary substation (TSO-DSO interface) for the installation of shared ESSs.
- *min_pe_factor*: Minimum power capacity to energy capacity ratio of the shared ESS. This constraint is related to the type of battery technology used, e.g., Li-Ion batteries typically have a minimum power capacity to energy capacity ratio of 0.1
- *max_pe_factor*: Maximum power capacity to energy capacity ratio of the shared ESS. This constraint is related to the type of battery technology used, e.g., Li-Ion batteries typically have a maximum power capacity to energy capacity ratio of 4.0

If no information is provided, it is assumed that the budget available is 1 Mm.u., the maximum energy capacity that can be installed per bus is 2.50 MVAh, and the minimum and maximum power capacity to energy capacity is 0.10 and 4.00, respectively.

The *Shared ESS Parameters* file contains the following information related to the solver:

- *solver*: name of the solver to be used to solve the SMOPF problem. In the example of Figure 9, the IpOpt [22] solver is used
- *linear_solver*: name of the linear solver to be used. This parameter is only applicable to solvers that support this feature, e.g., IpOpt [22] and Bonmin [23]. In the example of Figure 8, HSL ma57 solver is used [24]
- *solver_path*: path to the solver used to solve the ESSO's problem
- *verbose*: when this flag is set, detailed information regarding the solving procedure is displayed to the screen.

The *Shared ESS Parameters* file contains the following information related to the output options:

- *plot_results*: Flag that indicates if the shared ESSs results should be plotted or not
- *print_results_to_file*: Flag that indicates if the SMOPF results should be printed to an excel output file or not

If no information is given regarding the output options, it is assumed that the results should not be plotted or printed to an output excel file.

4.6.1.2. *Shared ESS Data file*

The *Shared ESS Data* file is an excel file that contains information regarding the operational data of the shared ESSs. The *Shared ESS Data* file must contain the following sheets:

- One sheet named “Scenarios”, where the information regarding the number and probability of the operational scenarios is defined
- One sheet named “Investment Cost” where the forecasted unitary power capacity and energy capacity costs are listed, for all the years of the planning horizon, in m.u./MVA and m.u./MVAh, respectively
- One sheet per representative year and day for upward and downward reserve activation, containing information for all scenarios defined in sheet “Scenarios”.

4.6.2. *Network* Information

The input data related to the networks should be placed in a directory with the network’s name. The network’s information consists of three types of files:

- *Network* files: contains information regarding the network’s topology and existing assets. One *Network* file should exist per representative year of the planning horizon.
- *Network Parameters* file: file where information regarding the SMOPF parameters is specified.
- *Network Data* files: contains information regarding the operational data of the network. One *Network Data* file should exist per representative year of the planning horizon.

4.6.2.1. *Network File*

The network files are given in MATPOWER format files [25]. In the scope of the ATTEST project, it was assumed that these files can be extended to consider additional information, not included in the MATPOWER specification. Such information includes the types of generators, additional information related branches, energy storages, etc. Further details are given in D2.3. The *Network* files should follow the “<network_name>_<year>.xlsx” naming scheme.

4.6.2.2. *Network Parameters file*

The *Network Parameters* file contains information to be considered in the execution of the SMOPF, solver parameters, and information related to the tool’s outputs. Figure 9 shows an example of the *Network Parameters* file corresponding to network “Location_1” of the example of Figure 6.

```
obj_type = COST
transf_reg = True
es_reg = True
fl_reg = True
rg_curt = False
l_curt = False
enforce_vg = False
slack_line_limits = False
slack_voltage_limits = False
solver = "ipopt"
linear_solver = "ma57"
solver_path = "C:\Lib\optim\dist\bin\ipopt.exe"
solver_tol = 1e-6
verbose = False
print_to_screen = False
plot_diagram = False
print_results_to_file = True
```

FIGURE 9 – SHARED RESOURCES PLANNING. NETWORK TEST CASE DEFINITION. *NETWORK PARAMETERS* FILE.

The *Network Parameters* file contains the following information related to network operation:

- *obj_type*: Objective type. *obj_type* can assume one of three values: “COST”, “LOSSES”, or “CONGESTION_MANAGEMENT”. “COST” sets the objective of the SMOPF to cost minimization; “LOSSES” to active power losses minimization; and “CONGESTION_MANAGEMENT” to congestion management, i.e., to minimization of the slack variables’ associated with line overloading; voltage magnitude violations; renewable and load curtailment, etc.
- *transf_reg*: Flag that indicates if OLTC transformers are controllable or not
- *es_reg*: Flag that indicates if ESSs are controllable
- *fl_reg*: Flag that indicates if flexible loads are controllable
- *rg_curt*: Flag that indicates if renewable generators are curtailable
- *l_curt*: Flag that indicates if loads are curtailable
- *enforce_vg*: Flag that indicates if the conventional generators located in PV buses control the voltage magnitude at their terminals
- *slack_line_limits*: Flag that indicates if slack variables related to lines’ overloading are to be considered. If these are to be considered, these violations (slack variables) are penalized in the objective function
- *slack_voltage_limits*: Flag that indicates if slack variables related to nodes’ voltage magnitude are to be considered. If these are to be considered, these violations (slack variables) are penalized in the objective function

If no information is given regarding network operation parameters, it is assumed that: (i) the objective is to minimize cost (for TN) and congestion management (for DNs); (ii) transformers, ESSs and flexible loads are controllable; (iii) renewable generators and loads are not curtailable; (iv) conventional generators do not control voltage at their terminals; and (v) slack variables related to voltage magnitude and line overload violations are not considered.

The *Network Parameters* file contains the following information related to the solver:

- *solver*: Name of the solver to be used to solve the SMOPF problem. In the example of Figure 9, the IpOpt solver is used

- *linear_solver*: Name of the linear solver to be used. This parameter is only applicable to solvers that support this feature, e.g., IpOpt [22] and Bonmin.[23] In the example of Figure 9, HSL ma57 solver is used[24]
- *solver_path*: Path to the solver used to solve the SMOPF problem
- *verbose*: when this flag is set, detailed information regarding the solving procedure is displayed to the screen

If no information is provided, IpOpt solver is selected with the HSL ma57 linear solver; and verbose flag is set to False.

The *Network Parameters* file contains the following information related to output options:

- *print_to_screen*: Flag that indicates if network information should be displayed to the screen
- *plot_diagram*: Flag that indicates if the network diagram should be plotted
- *print_results_to_file*: Flag that indicates if the SMOPF results should be printed to an excel output file or not

If no information is given regarding the output parameters, it is assumed that the network information is not displayed to the screen; the network's diagrams are not printed; and that the results are printed to an excel output file. If the *plot_diagram* option is selected, the network diagram is exported to a folder named "Diagrams" in the test case's directory, with the name "<network_name>_<year>.pdf". If the *print_results_to_file* option is selected, the network's SMOPF results are printed to a folder named "Results" in the test case's directory with the name "<network_name>_results.xlsx".

4.6.2.3. Network Data file

The *Network Data* file is an excel file that contains information regarding the operational data of the network. It is assumed that there is one *Network Data* file per year in the test case directory corresponding to the *Network*'s test case with the designation "<network_name>_<year>.xlsx".

The *Network Data* file must contain:

- One sheet named "Scenarios", where the information regarding the number and probability of the operational scenarios is defined
- One sheet per representative day and scenario which includes the active power load, reactive power load, upward flexibility, downward flexibility, and flexibility costs.

If renewable generators are present in the network, additional sheets should exist with the active and reactive power generation (also per representative day and scenario).

4.6.3. *Market Data* Information

Market Data information is given in separate excel files, one per year, as described in subsection 4.4. These files should be placed in a dedicated folder, named "Market Data," and follow the designation "<market_data_file_prefix>_<year>.xlsx".

The *Market Data* file must contain:

- One sheet named “Scenarios”, where the information regarding the number and probability of the market scenarios is defined
- One sheet per representative day for active power costs, reactive power costs, secondary reserve costs, and upward and downward tertiary reserve costs.

The market design considered by the tool is based on the Portuguese reserve market pricing scheme, i.e., secondary reserve capacity is paid at secondary reserve cost, and its activation (upward or downward) is paid at tertiary reserve costs (upward and downward, respectively). Conventional generators are paid per active and reactive power generation.

4.7. Output Data

The output of the optimization tool for planning TSO/DSO shared technologies is an excel file with detailed information regarding the planning procedure. The output file is exported to directory “Results”, with the name “<test_case>_planning_results.xlsx”.

The results file consists of the following sheets:

- “Main Info”: Contains the main information regarding the planning problem, i.e., objective function values, execution time, number of representative years and days, and number of market and operational scenarios
- “Capacity Investment”: Contains information regarding investments in power capacity per node, energy capacity per node, and the corresponding costs, for all the representative years in the planning horizon
- “Capacity Available”: Contains information regarding the power capacity per node, energy capacity per node, and daily energy capacity degradation for all the representative years in the planning horizon
- “ESS Secondary Reserve”: Contains information regarding the secondary reserve bands supplied by the shared ESSs, per representative year, day, and type (i.e., upward and downward)
- “Convergence Characteristic”: Contains information regarding the evolution of the lower and upper bounds of the bi-level planning optimization problem
- “OF Values”: Contains information of the objective function values obtained for each agent involved in the planning process, discriminated per representative year and day
- “Shared ESS”: Contains information regarding the shared ESSs’ active power, State-of-Charge (SoC), and upward and downward reserve, discriminated per node, representative year, representative day, market scenario, and operation scenario
- “Interface PF”: Contains information regarding the active and reactive power flows at the interface nodes between TN and DNs. This information is discriminated per operator (TSO or DSO), representative year, representative day, market scenario, and operation scenario
- “Voltage”: Contains information regarding the voltage magnitude and angle for all the networks involved in the optimization process. This information is discriminated per network, node, representative year, representative day, market scenario and operation scenario
- “Consumption”: Contains information regarding active and reactive power consumption, upward and downward flexibility, and active power curtailment for all networks involved in the optimization process. This information is discriminated per network, node, representative year, representative day, market scenario, and operation scenario

- “Generation”: Contains information regarding active and reactive power generation, and active power curtailment for all networks involved in the optimization process. This information is discriminated per network, generator, representative year, representative day, market scenario, and operation scenario
- “Branch Losses”: Contains information regarding branches’ active power losses, for all networks involved in the optimization process. This information is discriminated per network, branch (“from” bus and “to” bus), representative year, representative day, market scenario, and operation scenario
- “Transformer Ratio”: Contains information regarding the transformation ratio of OLTC transformers, for all networks involved in the optimization process. This information is discriminated per network, transformer (“from” bus and “to” bus), representative year, representative day, market scenario, and operation scenario
- “Branch Current”: Contains information regarding the branches’ current, in absolute value and percentage of the rated capacity, for all networks involved in the optimization process. This information is discriminated per network, branch (“from” bus and “to” bus”), representative year, representative day, market scenario, and operation scenario.

For the “Shared ESS”, “Interface PF”, “Voltage”, “Consumption”, “Generation”, “Branch Losses”, “Transformer Ratio” and “Branch Current” sheets, additional information regarding the expected values is provided (i.e., weighed by the probability of occurrence of each scenario). In section 8.1 are provided some examples of the tool’s outputs.

5. Test Case

In this section we show some illustrative results of the TSO-DSO shared resources planning tool. The test case shown is the same as the one in the examples of chapter 4, i.e., Croatian network corresponding to the Koprivnica region.

5.1. Test Case Description

The tool was run for the test case “HR1”, used as an example in chapter 3, following the procedure described in section 4.2. Test case “HR1” comprises of the Croatian transmission network “Location1”, corresponding to Koprivnica region, and DNs “A_BJ_35”, and “A_KPC_35”. To note that the DNs total a five of radially operated networks, two for “A_BJ_35” and three for “A_KPC_35”. The test case will be shared in the project’s repository.

Distribution network “A_BJ_35” is connected to nodes 55 and 68 of the transmission network, distribution network “A_KPC_35” is connected to nodes 29, 1, and 19. A total of four representative years were considered (2020, 2030, 2040, and 2050), and one representative day per year -- at the time of writing of this document, there was only one representative day available for the transmission network. The ATTEST’s dataset will be enriched with further data soon, that will be shared in the project’s repository. Two market scenarios were considered (common to TSO, DSOs, and ESSO), and five operational scenarios for the TN, DNs, and shared ESS. It was assumed that the load would grow at a yearly average rate of 1.25%, the flexibility would grow at an average rate of 5.00%, and the flexibility cost would grow at an average rate of 1.00% per year. Regarding the market data, it was adopted a growth factor of 1.25% for all prices. It was considered a value of 3% for the discount factor for the planning period.

It was considered that the investment budget was 1M€, the minimum and maximum power to energy capacity ratios are 0.10 and 0.40, respectively (corresponding to Li-Ion batteries), and it was considered that maximum energy capacity per shared ESS is 2.50 MVAh. In Table 1 are shown the unitary power and energy capacity costs adopted for the planning period.

TABLE 1 – SHARED RESOURCE PLANNING. TEST CASE “HR1”. UNITARY INVESTMENT COSTS.

CAPACITY COST	2020	2030	2040	2050
Power, [€/MVA]	69000,00	39600,00	34800,00	29800,00
Energy, [€/MVAh]	276000,00	158400,00	139200,00	119200,00

The prices of Table 1 were estimated from NREL’s cost projections for utility-scale battery storage report, mid scenario [26]. As it is possible to see, NREL forecasts that battery ESS costs will decrease significantly until 2030. After 2030 and until 2050 the battery ESS costs will continue to decrease, but at a much slower rate.

5.2. Network Diagrams

As it was previously described, the TSO-DSO shares resources planning tool can plot simplified network diagrams. Figure 10 shows the diagram of the transmission network used in the example test case, "Location1", for the year 2020.

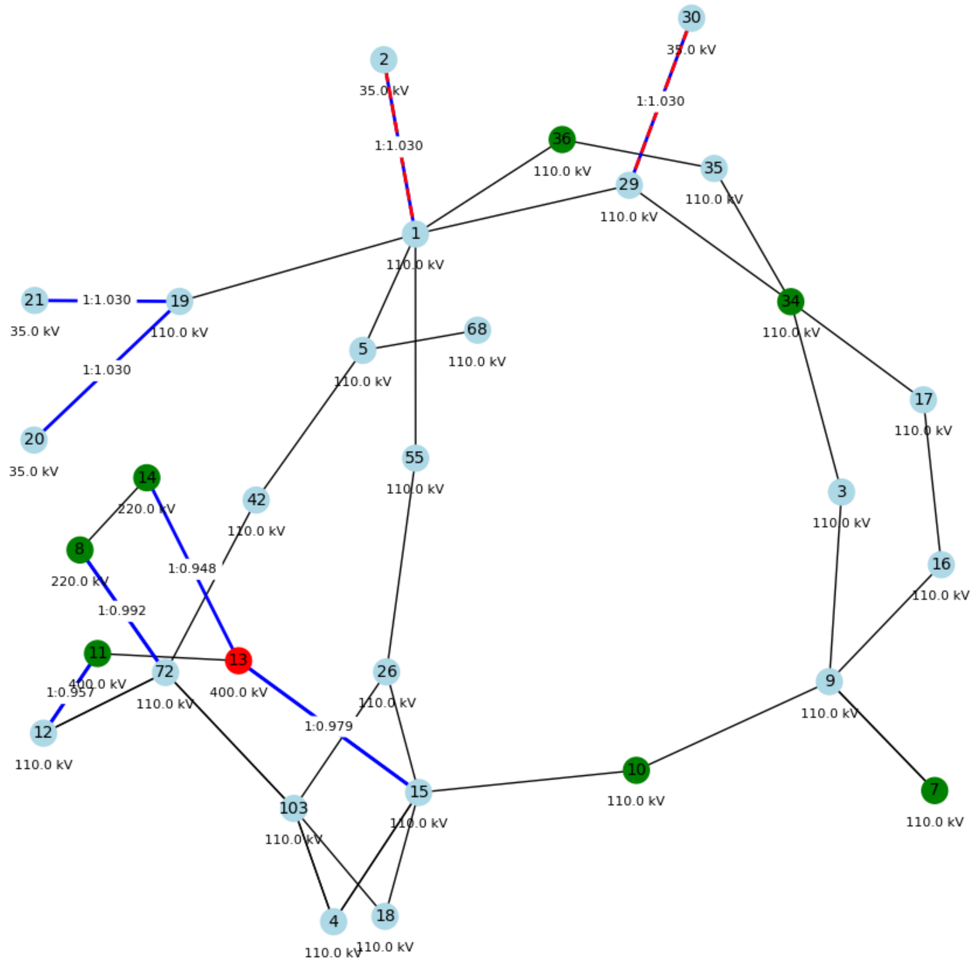


FIGURE 10 - SHARED RESOURCES PLANNING. EXAMPLE OF NETWORK DIAGRAM (NETWORK "LOCATION1").

This feature might be helpful to the user, as it allows to visualize the network's topology; easily identify open branches (red dashed lines); transformers (solid blue lines) and corresponding transformation ratio; and the types of the buses (slack bus in red, PV buses in green, PQ buses in light blue) and corresponding voltage levels.

5.3. Shared ESS Planning Results

The TSO-DSO shared resources planning tool was run on a desktop computer with a 4-core Intel Xeon E3-1245 v5 (3.5 GHz) processor, and 32 GB of memory. In the following subsection some illustrative examples of the tool's outputs are shown.

5.3.1. Convergence Characteristic

The problem took a total of 104 iterations and 53,948.63s (~15h) to converge considering a relative tolerance of 0.10%. Figure 11 shows the convergence characteristic of the bi-level planning problem (evolution of upper and lower bounds).

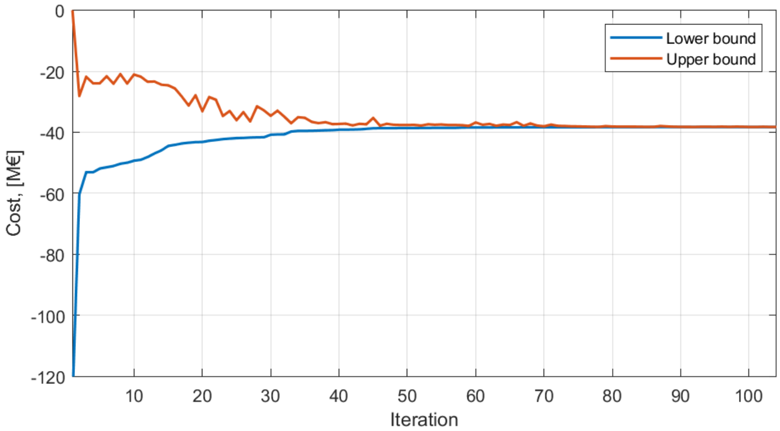


FIGURE 11 - SHARED RESOURCE PLANNING RESULTS. TEST CASE "HR1". CONVERGENCE CHARACTERISTIC.

5.3.2. Investment Plan

The ESSO's estimated profit over the planning horizon is 38.24 M€. Table 2 shows the power capacity and energy capacity invested per node and year of the planning horizon.

TABLE 2 - SHARED RESOURCE PLANNING RESULTS. TEST CASE "HR1". INVESTMENT PLAN

NODE ID	CAPACITY	2020	2030	2040	2050
55	Power, [MVA]	0.000	0.015	2.964	0.000
	Energy, [MVAh]	0.000	0.004	2.404	0.000
68	Power, [MVA]	0.000	0.015	3.343	0.000
	Energy, [MVAh]	0.000	0.004	2.496	0.000
29	Power, [MVA]	0.000	0.000	0.588	0.000
	Energy, [MVAh]	0.000	0.000	0.708	0.000
1	Power, [MVA]	0.000	0.000	2.090	0.000
	Energy, [MVAh]	0.000	0.000	1.759	0.000
19	Power, [MVA]	0.000	0.001	3.348	0.000
	Energy, [MVAh]	0.000	0.000	2.500	0.000

As it is possible to see from Table 2, the ESSO has the tendency to invest towards the end of the planning period. This can be explained by the fact that the investment costs will significantly decrease over the planning horizon due to discounting (see Table 1), and it was considered that the market prices will continue to increase. However, since the ESSs have a calendar life of 20 years, the ESSO opts for installing the ESSs in the year of 2040, instead of 2050, to maximize the utilization of the shared ESSs.

It is also possible to see that the ESSO invests in the year 2030, but in relatively small ESSs when compared to the year 2040. In year 2030 are installed in node 55 and node 68 ESSs with similar capacities of 15 kVA/3.80 kVAh, and in node 19 is installed an ESS with 1.32 kVA/0.33 kVAh. In year 2040 shared ESSs are installed in all of the interface nodes.

5.3.3. Transmission-Distribution Interface

5.3.3.1. Expected Interface Power Flows

Figure 12 shows the expected interface power flow at node 68 (transmission network), for the four representative years considered in the planning horizon. The TSO's requested power is shown in bold lines, and the DSO's requested power is shown in dashed lines.

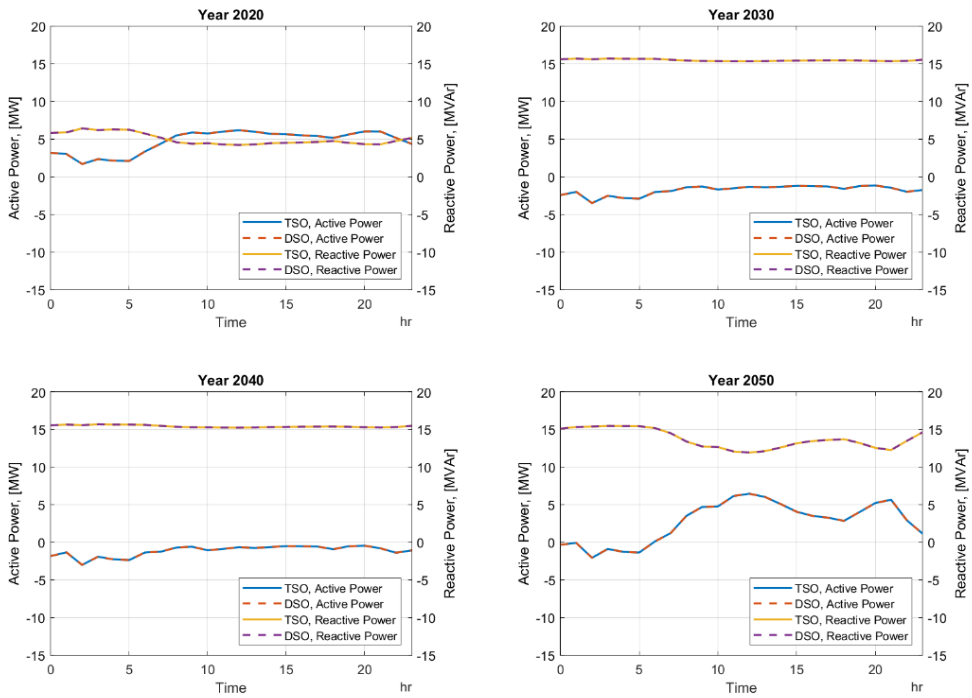


FIGURE 12 – SHARED RESOURCE PLANNING RESULTS. TEST CASE "HR1". INTERFACE POWER FLOW RESULTS OVER THE PLANNING PERIOD FOR NODE 68.

As it is possible to see from Figure 12, TSO and DSO reach a consensus regarding the active and reactive power flow at the TSO-DSO interface, for all the representative years of the planning horizon. Furthermore, it is also possible to see how the active and reactive power flow profiles evolve over the planning horizon. The active power consumption increases significantly between 2020 and 2030; remains relatively constant between 2030 and 2040; and, in the year 2050, shows a decrease in the middle of the day. It is also possible to see that the reactive power flow profile changes significantly over the planning period. It decreases from 2020 to 2030; remains relatively constant between 2030 and 2040; and increases again in 2050. This fact might be related to reactive power support required by the TSO, for voltage control purposes. In Figure 19, Figure 20, Figure 21, and Figure 22 of annex section 8.1 the active and reactive power flow profiles at the transmission-distribution interface for nodes 1, 19, 29, and 55, respectively, are shown, are shown.

5.3.3.2. Expected Interface Voltage Magnitude

Figure 13 shows the expected voltage magnitude for all the interface nodes and all representative years of the planning horizon.

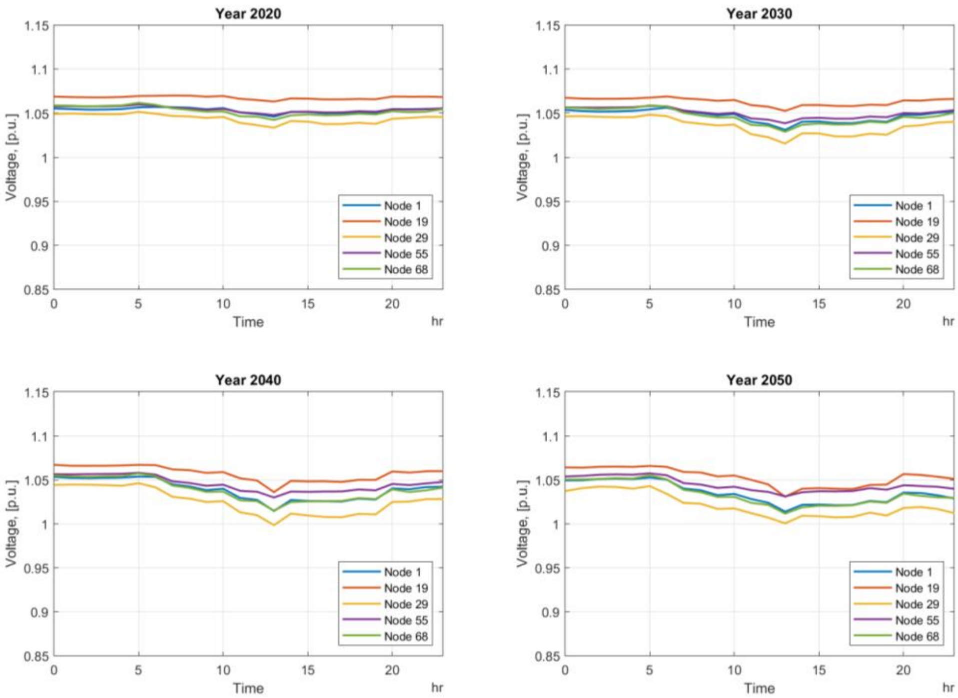


FIGURE 13 - SHARED RESOURCE PLANNING RESULTS. TEST CASE "HR1". INTERFACE VOLTAGE MAGNITUDE RESULTS OVER THE PLANNING PERIOD FOR ALL NODES.

As it is possible to see from Figure 13, the voltage magnitude fluctuations at the interface nodes between transmission and distribution networks increase significantly over the years (but staying within statutory limits). This is specially observed between the years 2020 and 2030, and between 2030 and 2040. Between 2040 and 2050, the voltage magnitude fluctuations remain approximately constant. This might be related to the reactive power support provided by the DSO, as it was discussed in subsection 5.3.3.1.

5.3.4. Shared Energy Storage Systems

5.3.4.1. Secondary Reserve

Figure 14 shows the expected secondary reserve bands supplied by the ESSO. To note that the upward secondary reserve is double of the downward secondary reserve, according to the Iberian Electricity Market (MIBEL) splitting rule.

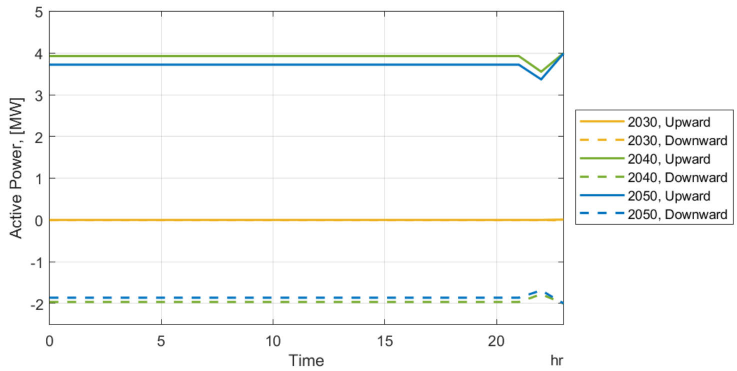


FIGURE 14 - SHARED RESOURCE PLANNING RESULTS. TEST CASE "HR1". TOTAL SECONDARY RESERVE BANDS SUPPLIED BY THE ESSO.

As it is possible to see from Figure 14, the secondary reserve band supplied by the ESSO in 2030 is very small, due the small size of the shared ESSs installed. The ESSO supplies the highest value in 2040, when most of shared ESS capacity is installed. In 2050, the secondary reserve bands supplied by the ESSO decrease, due to the energy capacity degradation experienced by the shared ESSs.

5.3.4.2. *Active Power and State-of-Charge*

Figure 15 shows the expected active power and SoC of the shared ESSs for the four representative years considered in the planning horizon. As it was previously reported, in the year 2020 no capacity was installed. In the year 2030, it is possible to see that although three relatively small shared ESSs were installed in nodes 19, 55 and 68, these do not participate in the energy market. This can be derived from the fact that it is more profitable to the ESSO to participate only in the secondary reserve market, and that TSO and DSOs do not need the shared ESSs to solve problems in their own networks. In the years 2040 and 2050, it is possible to see that the shared ESSs participate in the energy market.

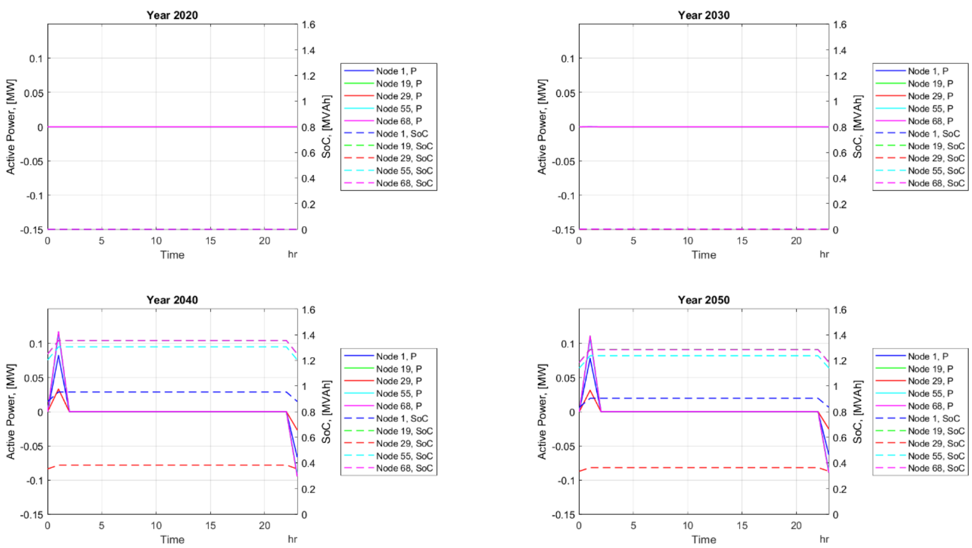


FIGURE 15 – SHARED RESOURCE PLANNING RESULTS. TEST CASE "HR1". SHARED ESSS ACTIVE POWER AND SOC.

5.3.5. Network Results

5.3.5.1. Expected Voltage Magnitude

Figure 16 shows the voltage magnitude values of the TN's nodes that are the closest to violate the admissible limits, for all the representative years considered in the planning horizon. The voltage magnitude upper and lower bounds are plotted in red dashed lines.

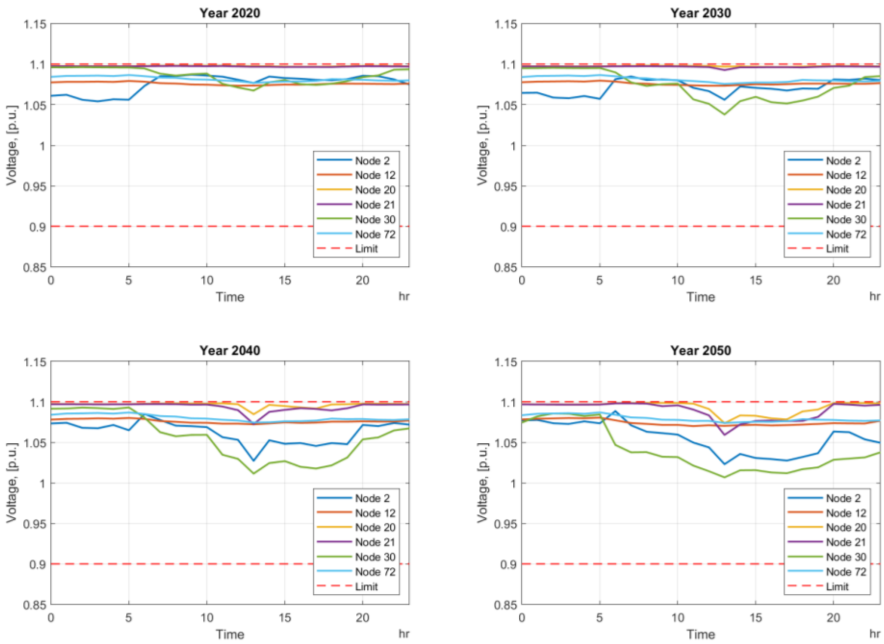


FIGURE 16 - SHARED RESOURCE PLANNING RESULTS. TEST CASE "HR1". TRANSMISSION NETWORK. VOLTAGE MAGNITUDE VALUES .AT PROBLEMATIC NODES.

As it is possible to see from Figure 16, in year 2020 the voltage magnitude of the nodes presented are very close to violate the upper limit. This is specially observed for node 21, which voltage magnitude is kept at approximately 1.10 p.u. for the whole day. As the planning period goes by, it is possible to observe that the voltage magnitude of these nodes moves further away from the voltage magnitude upper limit. This can be explained by the fact that the flexibility available at the TN level increases over the planning horizon.

Figure 23, Figure 24, Figure 25, Figure 26, and Figure 27 of annex subsection 8.2 show the expected voltage magnitude for all nodes of the DNs participating in the coordination scheme, for all representative years of the planning horizon.

5.3.5.2. Flexible Consumers Flexibility

Figure 17 shows the flexibility required from flexible consumers by TSO and DSOs participating in the coordination scheme, for the representative days selected.

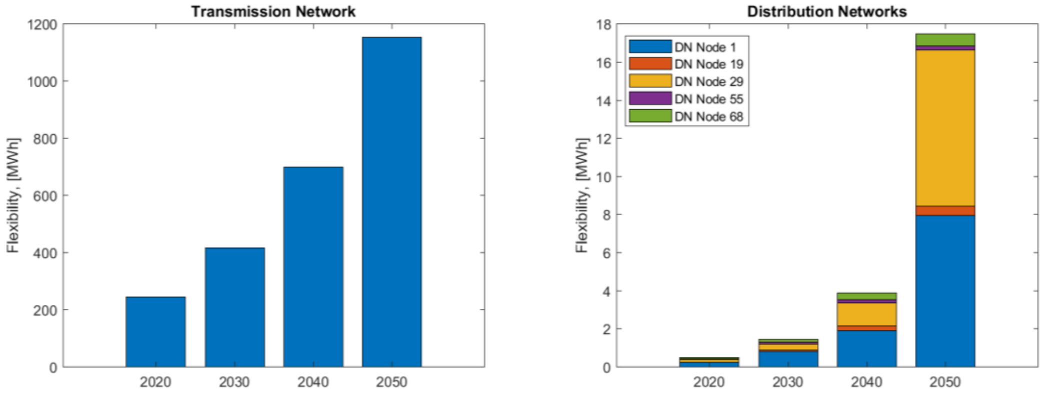


FIGURE 17 - SHARED RESOURCE PLANNING RESULTS. TEST CASE "HR1". FLEXIBILITY USAGE – TN AND DNS PARTICIPATING IN THE COORDINATION SCHEME.

As it is possible to see from Figure 17, the flexibility required from flexible consumers increases exponentially at the transmission and DN levels. However, the growth of flexibility usage is much more drastic at the DN level. This fact can be explained by the fact that the growing flexibility at the distribution level is used not only by DSOs for the management of their own network, but also to support the operation of the TN.

5.3.5.3. *Expected Losses*

Figure 18 shows the expected energy losses at the transmission and DN levels, for the representative days selected.

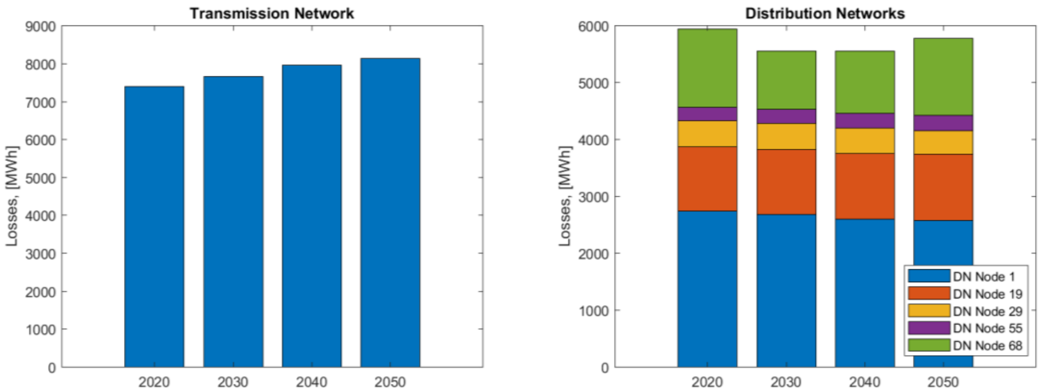


FIGURE 18 - SHARED RESOURCE PLANNING RESULTS. TEST CASE "HR1". FLEXIBILITY USAGE – TN AND DNS PARTICIPATING IN THE COORDINATION SCHEME.

As it is possible to observe from Figure 18, the growth of flexibility-providing resources brings benefits to grid operation, also in terms of network losses (although it is not a direct objective of the coordination scheme). At the transmission level, it is possible to observe that although the network losses increase over the planning period, these increase at a slower rate than the adopted load growth factor. At the distribution level, it is possible to observe that the network losses decrease between 2020 and 2040, increasing again in 2050 although a value lower than the one of 2020. This fact might be related to the fact that the network is operating closer to its limits in 2050.

6. Concluding Remarks

This deliverable presents the user guide of the optimization tool for planning of TSO-DSO shared technologies, developed in Task 3.3 of the ATTEST project. It includes:

- The specification of input and output data required and its format
- A user guide on how to run the tool from the command line, and
- Illustrative examples of the tool's output.

The tool will be publicly shared in ATTEST's toolbox along with the final report, D8.5 -- Final Report on Dissemination, Communication and Exploitation results, in the middle of 2023.

The proposed planning tool is developed from the perspective of a third-party investor, the ESSO, and has the objective of determining an optimal investment plan in shared ESSs, that can be simultaneously used by TSO and DSOs for the operation of their own networks. The tool is based on a bi-level optimization framework., where at the upper-level investment decisions are determined, and at the lower-level the operational planning is simulated, considering the TSO-DSO coordination mechanism adopted in ATTEST. The tool considers uncertainty derived from forecasts of market prices, load, RES generation and secondary reserve requirements, to make the results more robust in respect to future scenarios. The test case presented in this document will also be shared in ATTEST's toolbox, in addition to a set of other test cases developed within the ATTEST project and presented in D2.3.

7. References

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8. Annex

8.1. Shared Resource Planning Results – Interface Power Flow

Figure 19, Figure 20, Figure 21 and Figure 22 show the active and reactive power flows at the transmission-distribution interface for nodes 1, 19, 29, and 55, respectively, for all of the representative years considered in the planning horizon.

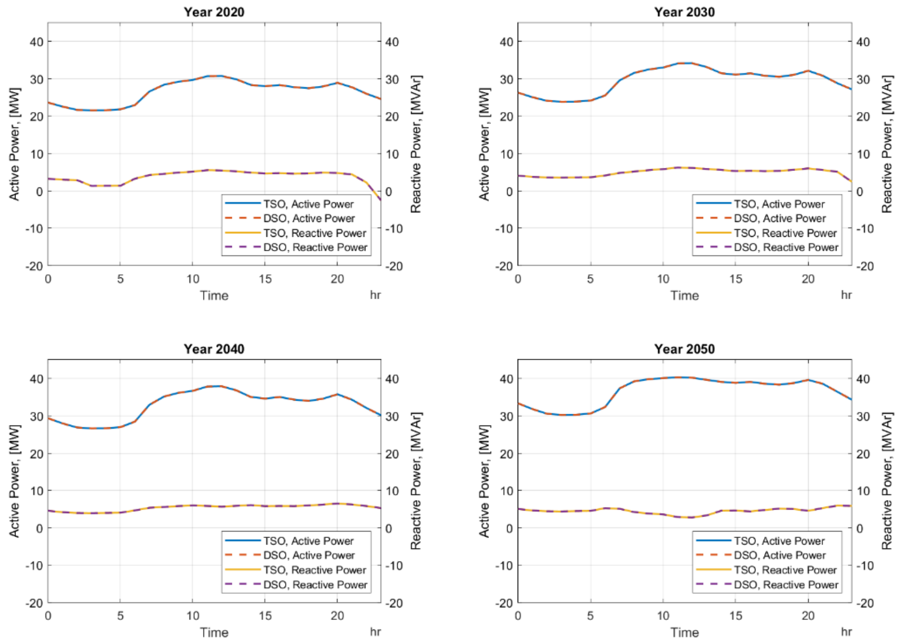

FIGURE 19 – SHARED RESOURCE PLANNING. TEST CASE "HR1". INTERFACE POWER FLOW, NODE 1.

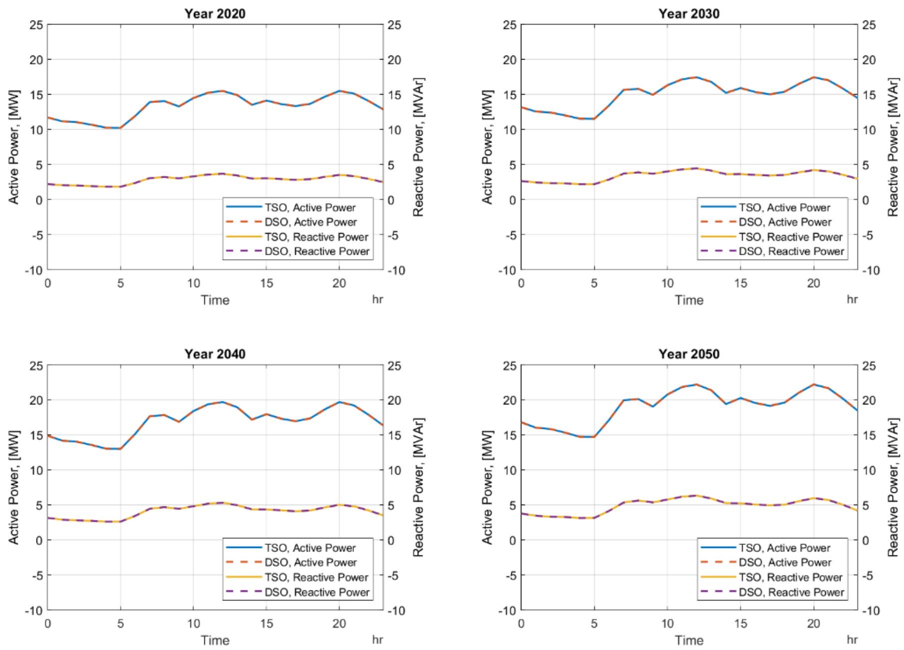

FIGURE 20 - SHARED RESOURCE PLANNING. TEST CASE "HR1". INTERFACE POWER FLOW, NODE 19.

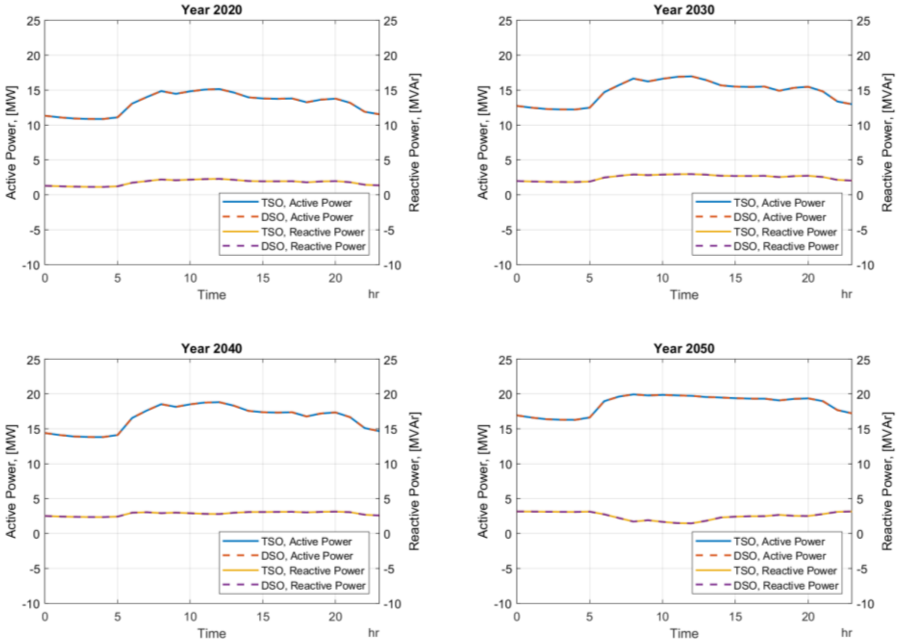

FIGURE 21 – SHARED RESOURCE PLANNING. TEST CASE "HR1". INTERFACE POWER FLOW, NODE 29.

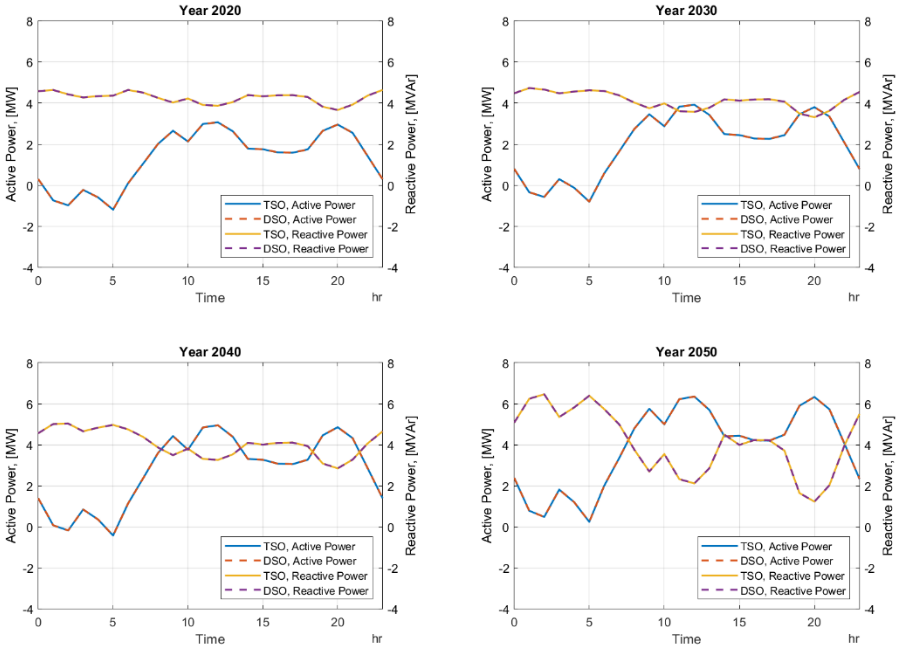

FIGURE 22 – SHARED RESOURCE PLANNING. TEST CASE "HR1". INTERFACE POWER FLOW, NODE 55.

8.2. Network Results – Expected Voltage Magnitude

Figure 23, Figure 24, Figure 25, Figure 26 and Figure 27 show the expected voltage magnitude for the distribution networks connected to nodes 1, 19, 29, 55 and 68 of the transmission network, respectively, for all the representative years considered in the planning horizon. The voltage limits are plotted in read dashed lines.

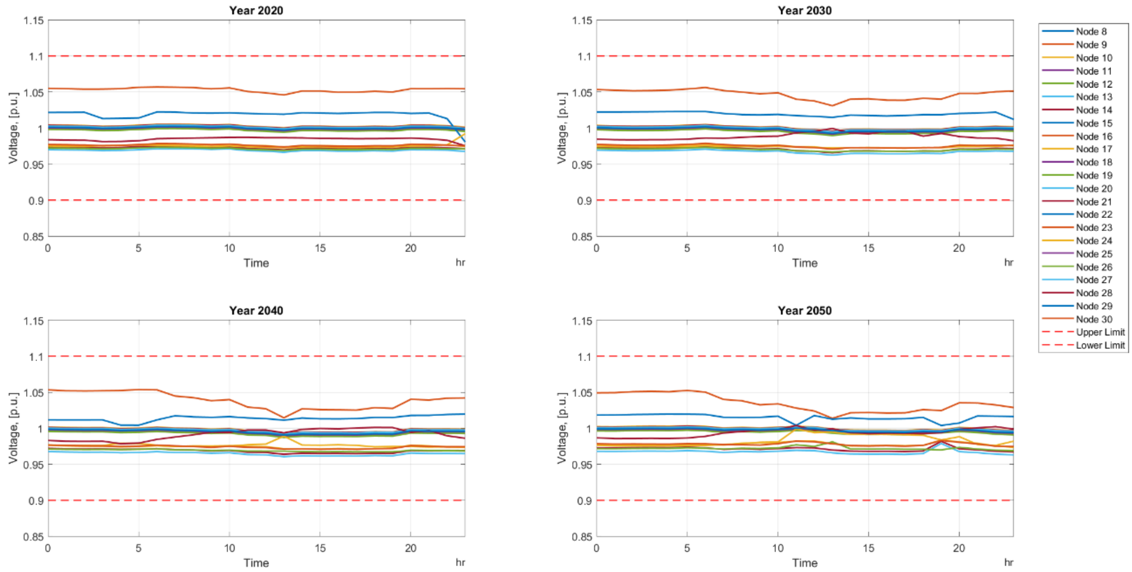

FIGURE 23 - SHARED RESOURCE PLANNING. TEST CASE "HR1". EXPECTED VOLTAGE MAGNITUDE, NETWORK "A_KPC_35_2" (TN NODE ID 1).

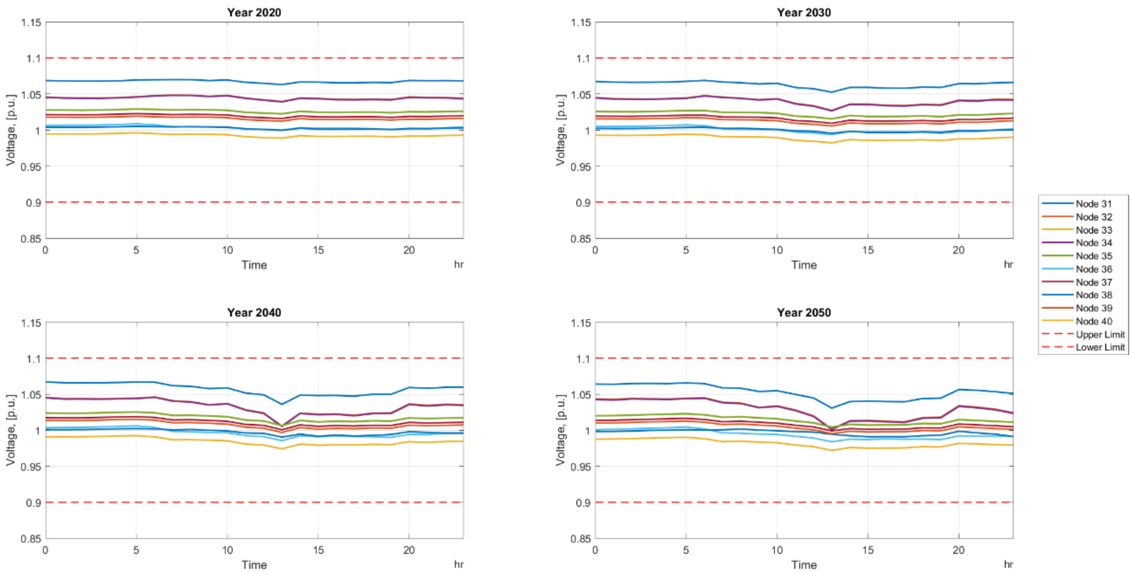

FIGURE 24 - SHARED RESOURCE PLANNING. TEST CASE "HR1". EXPECTED VOLTAGE MAGNITUDE, NETWORK "A_KPC_35_3" (TN NODE ID 19).

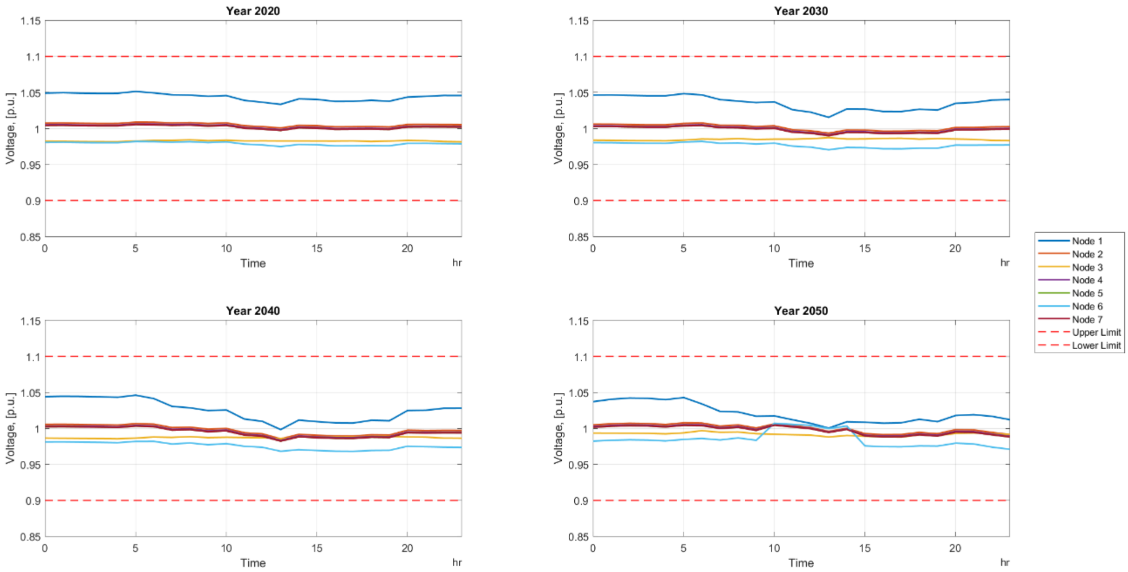

FIGURE 25 - SHARED RESOURCE PLANNING. TEST CASE "HR1". EXPECTED VOLTAGE MAGNITUDE, NETWORK "A_KPC_35_1" (TN NODE ID 29).

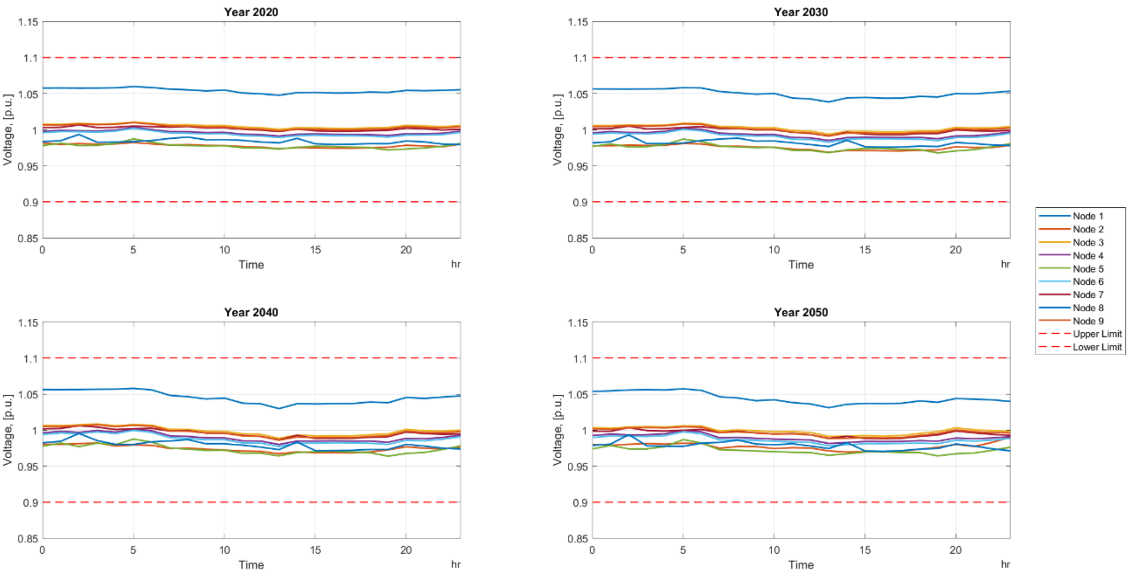

FIGURE 26 - SHARED RESOURCE PLANNING. TEST CASE "HR1". EXPECTED VOLTAGE MAGNITUDE, NETWORK "A_BJ_35_1" (TN NODE ID 55).

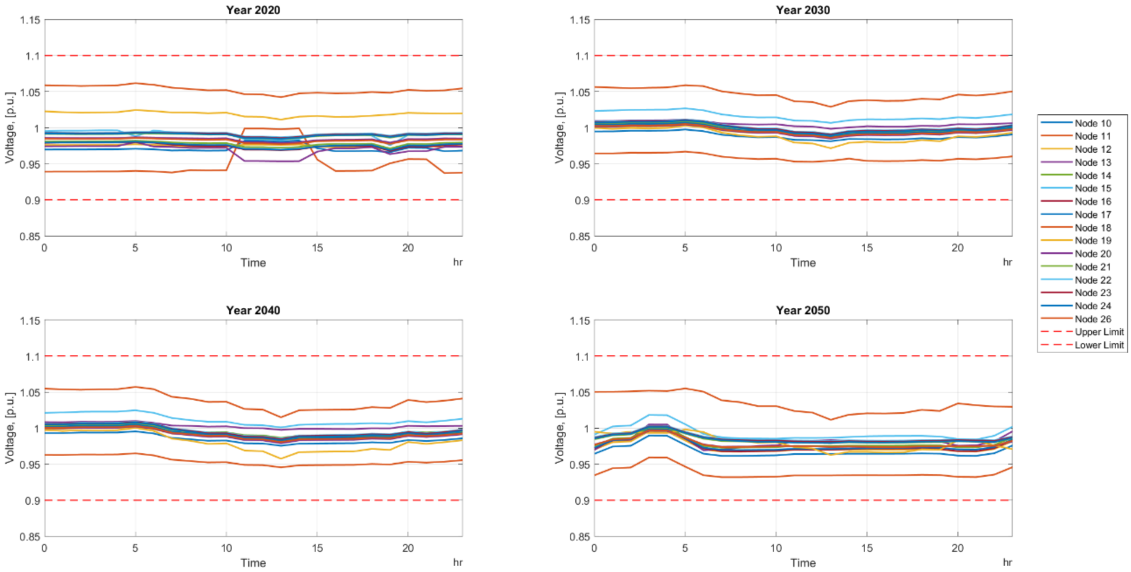

FIGURE 27 - SHARED RESOURCE PLANNING. TEST CASE "HR1". EXPECTED VOLTAGE MAGNITUDE, NETWORK "A_BJ_35_2" (TN NODE ID 68).