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The German Demonstration-Flexibility of Active and Reactive Power from HV Distribution Grid to EHV Transmission Grid

D6.7

EU-SysFlex

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

AB	Advisory Board
ARIMA	Autoregressive Integrated Moving Average
CA	Consortium Agreement
CGMES	Common Grid Model Exchange Standard
CIM	Common Information Model
DB	Demonstration Board
DER	Distributed Energy Resource
DSO	Distribution System Operator
DoA	Description of Action
EC	European Commission
EC-GA	Grant Agreement
EEG	
EHV	Extra High Voltage
EnWG	
EPSO	Evolutionary Particle Swarm Optimisation
EQ	Equipment profile
EU-SYSFLEX	Pan-European System with an efficient coordinated use of flexibilities for the integration of a large share of Renewable Energy Sources (RES)
FTPS	File Transfer Protocol Secure
GA	General Assembly
GCP	Grid Connection Points
GUI	Graphical User Interface
HV	High Voltage
ICT	Information and Communications Technology
KDE	Kernel Density Estimate
LSTM	Long-Short Term Memory
MO	Management Office
MOS	Model Output Statistics
MV	Medium Voltage
nRMSE	RMSE normalised with the specified nominal power of the wind farm
NWP	Numerical Weather Prediction
OLTC	On Load Tap Changer
PC	Project Coordinator
PG FHWM	Project Group of TSO and DSOs to define how to coordinate Frequency Control and Active Power Management
PMB	Project Management Board
p.u.	Per Unit
RES	Renewable Energy Sources
RMSE	Root Mean Square Error
SCP	Secure Copy
SSH	Steady State Hypothesis Profile
STATCOM	Static Synchronous Compensator
SV	State Variable profile
TM	Technical Manager
TP	Topology Profile

TSO	Transmission System Operator
WP	Work Package

EXECUTIVE SUMMARY

The German demonstration within EU-SysFlex has been set up in order to prove the feasibility of innovative congestion management and voltage control. The approach of the German demonstration is a combined and optimised active and reactive power management in the distribution grid. This not only allows the DSO to enhance efficiency in grid operation, but on the same time facilitating congestion management and voltage control support for the TSO. To reach these goals, schedule-based processes were designed and tested.

The concept of the German demonstration is on the one hand to meet the requirements of the regulatory framework to implement successful solution in daily operation, but on the other hand to develop solutions that also show benefits in a changed regulatory framework and proposes the needed changes.

The following benefits would be gained in using the developed Decision Support Tools in grid operation:

- Efficient schedule-based management of active and reactive power for redispatch and voltage control.
- Reduced active power flexibility need by integrating reactive power in the optimisation process.
- Reduced complexity for grid operator staff.
- Enhanced efficiency in grid operation by reducing grid losses.

The key to obtain these benefits is coordination between involved system operators. This design of coordination scheme of the German demonstration enhances the resiliency in strengthen the liability according to EU Directive 2019/944 and as proven, it shall be based on the following principles:

- Every system operator is responsible for its own grid.
- Every system operator predicts the available flexibility potential in its own grid.
- System operators from connected grids are being informed about available flexibility potential.
- Flexibility selection and activation is carried out by the system operator where the flexibility is connected.
- Both TSO and DSO needs and constraints are taken into account.

In case of insufficient coordination, experiences from the German demonstration evince the inaccuracy of optimisation results and therefore insecure decision-making in grid operation. The insecure decision-making leads to high security margins or high probability of additional emergency measures need. Such inefficient coordination contradicts the goal of an efficient grid operation.

The German demonstration has shown the feasibility of efficient schedule-based congestion management and voltage control with an approach that allows reduced data exchange complexity, i.e. the use of data thrift principles. In Germany, the regulatory framework obliges DSOs to exchange detailed information that the German demonstration has shown superfluous. With the approach of the German demonstration, higher level of aggregation leads to the same efficient decision-making and reduces the amount of information exchanged. This data thrift approach is based on the following principles, which also support the liability according to EU Directive 2019/944:

- Grid data always stays in the sphere of the respective system operator.
- Grid impact analysis remains the responsibility of the respective system operator.
- Data exchange is aggregated a much as possible to reduce complexity.

The following key messages can be condensed from the findings of the German demonstration within EU-SysFlex:

1. **The coordination of flexibility providing System Operator (SO) and flexibility demanding SO is key for an efficient use of flexibilities.**
2. **Efficient Schedule-based management of active and reactive power for redispatch and voltage control is feasible.**
3. **The accuracy of forecast is the most important factor for reliable prediction of network states.**
4. **The prediction of reactive power deviates more than active power.**
5. **The complexity for grid operators can be reduced by German demonstration's Decision Support Tools.**
6. **The efficiency of grid operation can be increased by approximately 5 %.**

1. INTRODUCTION

Today, the energy supply within the European energy system is undergoing significant changes due to the addition of renewable energy sources (RES), which are mainly integrated in distribution grids. As a result, it is followed by increasing decentralization and complexity of the power supply. This inevitably leads to high probability of widespread technical challenges such as line overloads, reverse energy flows, unforeseen congestions and sudden voltage violations. The renewable resources are characterized by a high level of fluctuation in power supply, which is crucial for grid operators such as DSOs and TSOs. Nevertheless, renewable generation units are gradually replacing conventional power plants due to relatively low energy cost and minimal harmful impact on the environment. In this regard, it becomes necessary to implement innovative system solutions, as well as effective measures and tools for the optimisation of the energy system with high share of RES, including further development in the energy market. This is the goal of EU-SysFlex.

1.1 WP6 GOALS AND TASK OF THE GERMAN DEMONSTRATION

Work package WP6 of EU-SysFlex has been designed to analyse the "Demonstration of flexibility services from resources connected to the distribution network". The resulting opportunities, arising from the decentralized flexible distribution network assets, enable a secure and safe power supply system, but need increased coordination between TSO and DSO. The primary goal of the German demonstration in the EU-SysFlex project is to enable the energy system to use flexibilities connected in the high voltage distribution system in an efficient and coordinated way. In order to achieve the defined goal, in-depth analysis are carried out, in particular, to tackle the identified technical deficiencies in developing effective tools with a focus on integrating and testing new system services in control centres of the distribution system operator. The German demonstration is led by the distribution system operator (DSO) MITNETZ STROM with the support of E.ON and the technical partners Fraunhofer IEE, university of Kassel and INESC TEC. The results achieved allow increasing usage of available flexibilities of power supply systems due to the enablement of active and reactive power flexibility usage coming from RES connected to the distribution grid for the needs of DSOs and TSOs.

1.2 SCOPE AND OBJECTIVES OF THIS DELIVERABLE

The aim of the German Demonstration is to enable the provision of flexibility services from DSO connected sources to the TSO, for the TSO's congestion management due to line loadings and voltage limit violation. In addition, the DSO itself is using the same services in order to sustain a stable and secure grid operation in the distribution grid. For these flexibility services, active and reactive power provision is managed from assets in the distribution grid. How this is developed, implemented and executed is described in this deliverable.

Primarily, conventional as well as RES generation units in the high voltage (HV) grid – in Germany namely 110 kV - would provide the aforementioned flexibility services. For active power flexibilities assets that are not directly connected to the HV grid but rather connected to lower voltage levels, can also be utilised in general – but were

not considered for the field tests. The flexibilities are not prioritised according to the voltage level but rather according to the effect on the congestion and the costs.

To realise this, the following detailed objectives were pursued:

- forecasting generation and consumption connected to the HV grid;
- predicting power flows in the HV grid, including possible power flows due to contracted capacities for frequency stability services which might be activated by the TSO;
- taking into account all grid constraints due to security reasons in the distribution grid including flexibility activation for congestion management in the distribution grid;
- providing information of the available flexibility potential of active power (day-ahead and continuous intraday update) and reactive power (intraday - up to 6 hours ahead expected) to the TSO;
- enabling the delivery of flexibility services and the execution of the TSO's calls for flexibility.

1.3 STRUCTURE OF THE DOCUMENT

The structure of the deliverable is as follows:

- Chapter 2 describes the actual situation in the Mitteldeutsche Netzgesellschaft Strom mbH (MITNETZ STROM) grid, introduces drivers and challenges and outlines the general objectives of the demonstration;
- Chapter 3 presents an overview of the development work done in the demonstration and explains the most important functionalities;
- Chapter 4 presents the outcomes of the field tests and the experience gained from the demonstration,
- Chapter 5 describes the conclusion and key messages of the German demonstration.

2. GENERAL OVERVIEW OVER THE DEMONSTRATION

The German Demonstration is being implemented in the HV (110 kV) distribution grid of MITNETZ STROM in the south of Brandenburg and Saxony-Anhalt and in the west and south of Saxony. In the grid area of MITNETZ STROM the installed capacity sums up to 10.2 GW of distributed energy resources (DER), of which more than 9.5 GW (i.e. more than 93%) are renewable energy resources (RES). The German demonstration uses an installed capacity of 5.5 GW of distributed assets connected to the HV grid, of which 4.3 GW are renewable. These available flexibilities will be offered to the TSO, who operates the extra-high voltage (EHV) grid of 220 kV and 380 kV. The Demonstration therefore includes 17 TSO/DSO interfaces at the EHV/HV interface with 43 transformers.

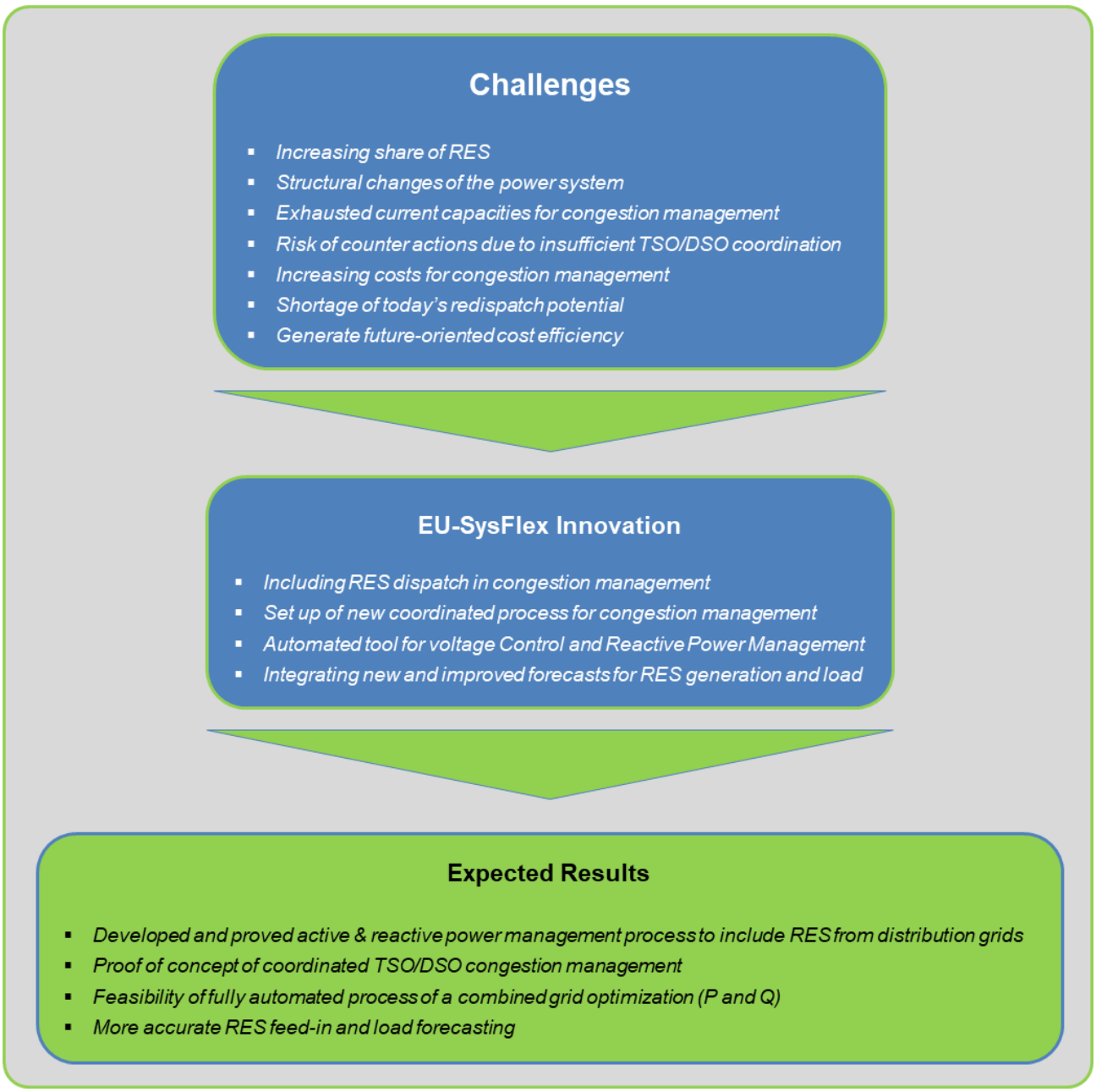

FIGURE 1 – OVERVIEW OF THE GERMAN DEMONSTRATION

Figure 1 provides a detailed overview of the innovations to tackle the challenges within the German demonstration, as well as the expected results. These points are described in detail in this chapter of the deliverable.

2.1 STATUS-QUO, DRIVERS AND CHALLENGES ADDRESSED BY THE DEMONSTRATION

In 2030, an even more increasing share of RES in the energy system is expected. High share of weather dependent fluctuating generation makes more efficient congestion management processes for both TSOs and DSOs necessary. Already today, events occur that cause congestions in the transmission and distribution grid.
While developing the German demonstration, regulation for congestion management has changed. New regulation is in action since 01. October 2021 and the following description is from perspective of the former regulation. In normal operation, foreseen congestions in the transmission grid are managed with redispatch measures according to § 13.1 of the German Energy Industry Act (Energiewirtschaftsgesetz – EnWG [1]) applied only to conventional power plants connected to the transmission grid. Formally, there is also the possibility to include conventional plants (> 10 MW) connected to the distribution grid in this process, but in reality this is rarely done. If the redispatch potential is not sufficient, the next step is the feed-in curtailment according to § 13.2 of the German Energy Industry Act. In this process feed-in from RES is reduced as an emergency measure. This curtailment is realized first via RES connected to the transmission grid, and only after that via RES connected to the distribution grid. The process is set up in such a way that the TSO issues a request for feed-in curtailment to the DSO. It is then the responsibility of the DSO to fulfil the measure. This process of the congestion management under former regulation regarding solving congestion in the transmission grid is visualized in Figure 2.

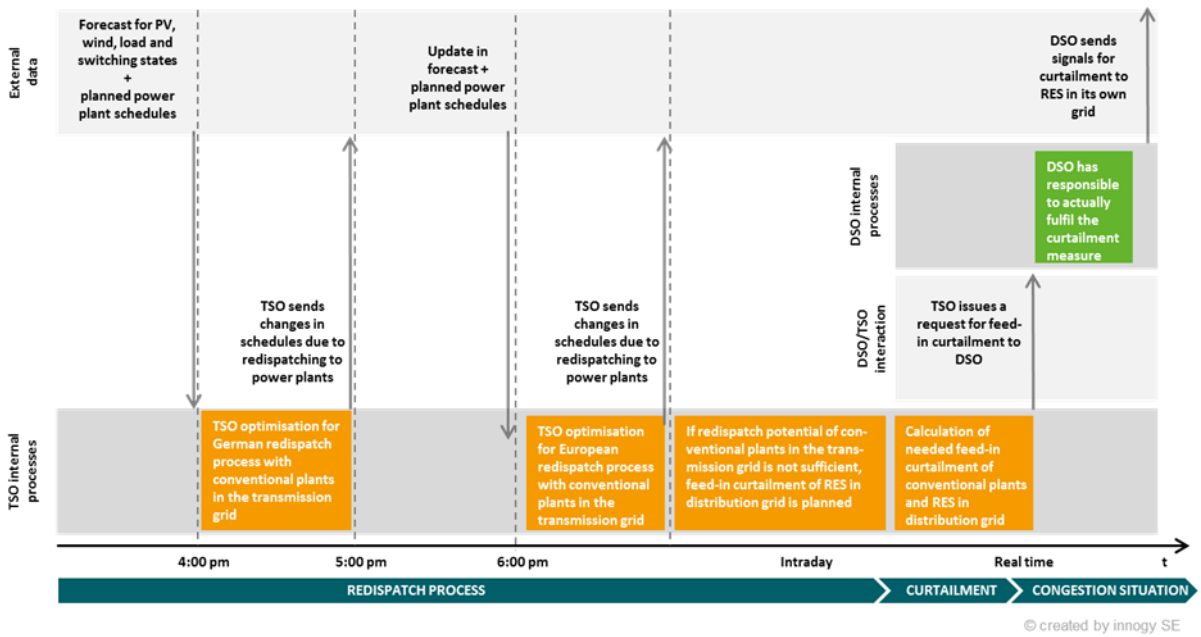

FIGURE 2 – PROCESS OF THE GERMAN CONGESTION MANAGEMENT BEFORE 01. OCTOBER 2021

The increasing share of RES and the additional delays in Germany's planned grid expansion projects make that transmission system operators (TSOs) already face challenges in day-to-day grid operation and operational

planning. It has become increasingly common that TSOs are forced to apply remedial measures at short notice such as redispatching in order to relieve grid congestions. In situations with high feed-ins of RES, a sufficient number of power plants suitable for redispatching in operation are not always available. The feed-in curtailments of RES according to § 13.2 of the German Energy Industry Act, which are supposed to be emergency measures, were used in addition. Unlike redispatch measures curtailment is not an energetically balanced measure and therefore needs additional balancing measures, such as balancing power. This has been resulting in compensational payments for curtailing RES plants and, in addition, payment for the balancing energy needed. This causes a double payment, although the congestion was predicted and foreseen. Furthermore, these former solutions to deal with shortage of congestion management measures for the transmission grid were reaching their technical and economic limits. The approach of the German demonstration for a innovative process of including RES, connected to the distribution grid, into schedule-based congestion management, means redispatch, is in line with the new regulation and is described in chapter 3.

Another challenge is related to the voltage control in the German grid. Today's voltage control at the interface between the TSO and the DSO consists of two tools. One tool is to activate/deactivate an inductor at the interface. The other tool is to use the on load tap changer (OLTC) on the EHV/HV transformer. Both tools are controlled by the TSO, but used in coordination with the DSO. The coordination process is done by phone. The operator who needs the flexibility calls the other party to coordinate the use of the flexibility. Detecting the need is close to real time. The DSO uses OLTC at HV/MV-substations as well with an automatic setting to adjust the voltage to a defined range in MV. Due to a large share of infeed from distributed energy resources (DER), the limited operating range of the OLTC is insufficient compared to the needed flexibility. The full potential of the OLTC is already in use for voltage control. Thus, additional methods of providing reactive power flexibility are needed.

Therefore, coordination and automation for these is required whenever the predicted voltage at the TSO/DSO interface is estimated to be out of the operational band meaning that the predicted voltage is either higher than the upper bound or lover than the lower bound. A generalized example is illustrated in Figure 3.

Dynamic local voltage control in the distribution grid is not considered as flexibility between TSO and DSO, although it has the potential to be a third tool. Today, TSOs can also adapt the power factor of big conventional power plants or grid assets like a phase shifter or Static Synchronous Compensator (STATCOM) for voltage control in the transmission grid and the DSO uses static settings or in some cases dynamic settings for local voltage control in distribution grid. If the voltage settings and the reactive power flow at the interface between TSO and DSO are within a defined range, there is no coordination between the two parties regarding reactive power management in the respective grid and the operators make sure to keep the settings in this range. The usage of these two existing tools for voltage control depends on the availability of a sufficient amount of reactive power flexibilities in extra high voltage (EHV). Dependencies on conventional plants in the EHV level does not fit into a future power system with an increasing share of RES that is mainly connected to the HV and lower voltage levels. These distributed energy resources (DER) are displacing and consequently decreasing the amount of flexibilities from EHV grid connected plants. The limited coordination between TSO and DSO regarding reactive power management leads to limited settings for voltage control.

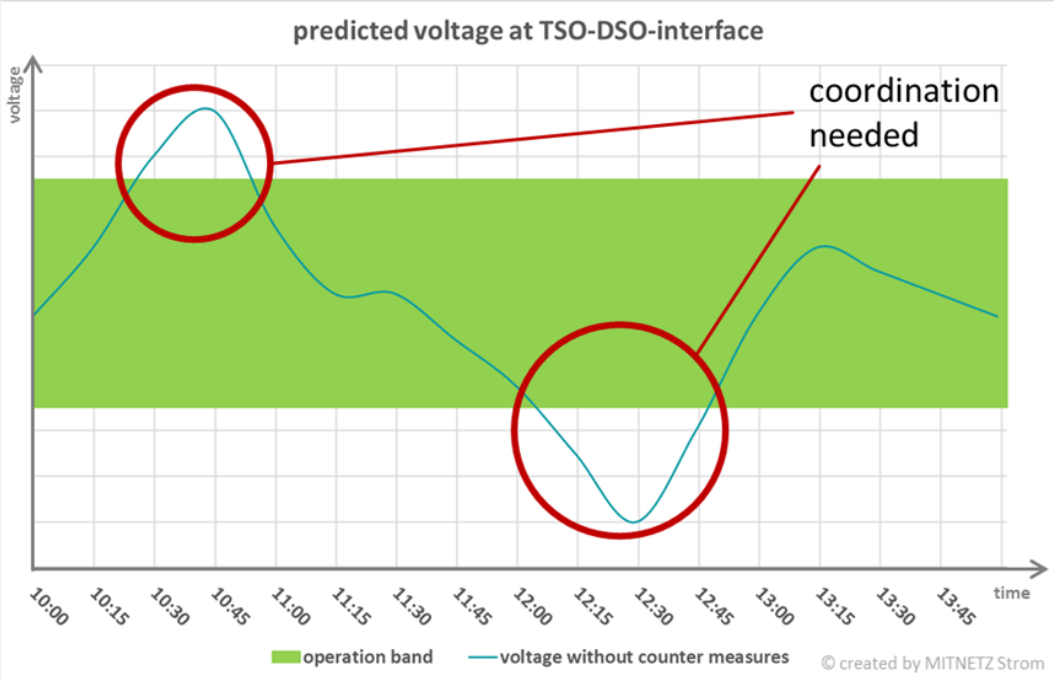

FIGURE 3 – PREDICTED VOLTAGE AT TSO/DSO INTERFACE

Multiple drivers constitute the basis for the German Demonstration, which can be distinguished between internal and external drivers. Internal drivers are situations, events or decisions that occur inside the business and are therefore under control of the company. External drivers on the other hand are situations, events or decisions that occur outside of the company. The external and internal drivers of the German Demonstration are displayed in Figure 4.

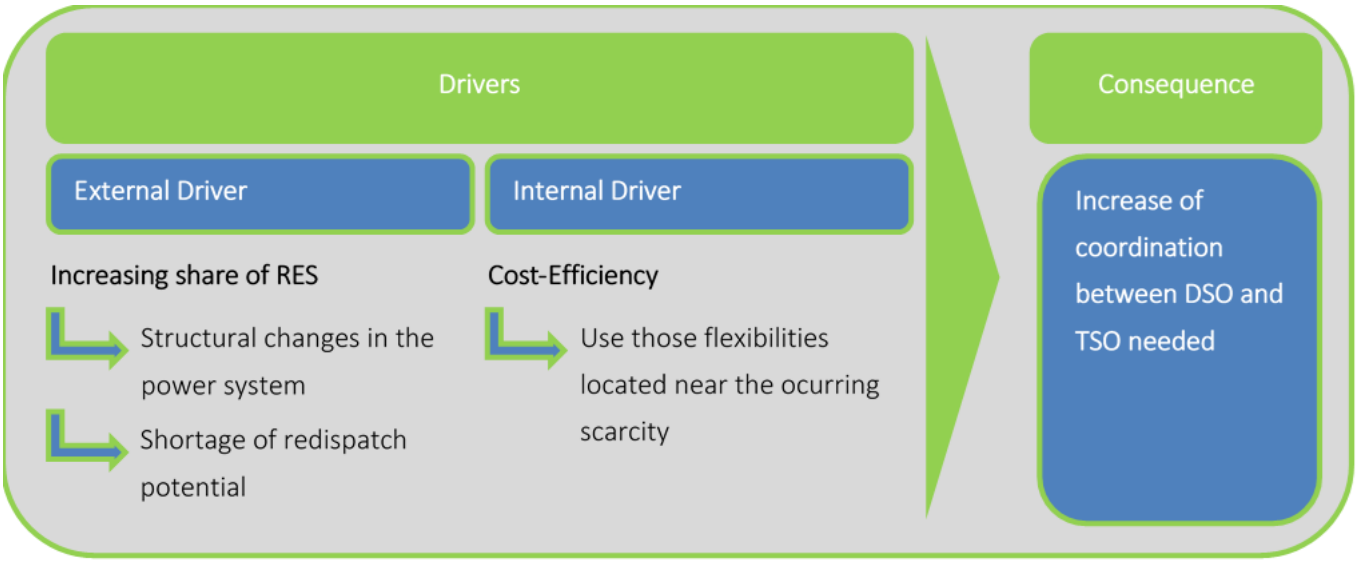

FIGURE 4 – DRIVERS FOR THE GERMAN DEMONSTRATION

Already in 2017 Germany had a share of roughly 40 % [2] of renewable energy resources (RES) regarding the net electricity generation. In 2030, an even higher share of RES is expected, as the government aims at 65% RES in 2030

as stated in the legal amendment of the German Renewable Energy Act (EEG) in 2017 [3]. This raising share of RES in the system leads to significant structural changes of the power system.

The generation from RES will continue to increase in the future, and therefore the number of conventional power plants will decrease and it will result in a more decentralised power system. Due to this, the flexibility potential in transmission grid will face a strong decrease. Therefore, some flexibilities will have to be provided by RES, a large share of which is connected to the distribution grid. In Germany, the distribution grid covers voltage levels from 110 kV down to low voltage. Most of the RES are connected to the same infrastructure as most of the consumption. The HV distribution grid is built as a meshed grid and this means that the sensitivity and impact of generation units on e.g. the interconnection to the TSO depend on load flow and grid topology.

This increasing share of distributed RES leads to higher requirements in congestion management for both TSO and DSO. Already today, events occur that cause congestion both in the TSO and in the DSO grids. An exemplary situation for that is when the use of conventional power plants in the distribution grid for reserve requirements (frequency control or frequency restoration) by the TSO causes congestion in the distribution grid. In this case, there is a risk that if TSO and DSO do not coordinate their actions, the DSO solves this congestion e.g. by reducing production of RES in the distribution grid, counteracting the measure for reserve requirements taken by the TSO.

The increase of the share of RES also leads to a shortage of today's redispatch potential. If units fed in as traded by commercial aggregators (who set the schedule) without the TSO performing redispatch (setting a new schedule), many lines would show congestion in the grid (see for example red transmission lines in Figure 5).

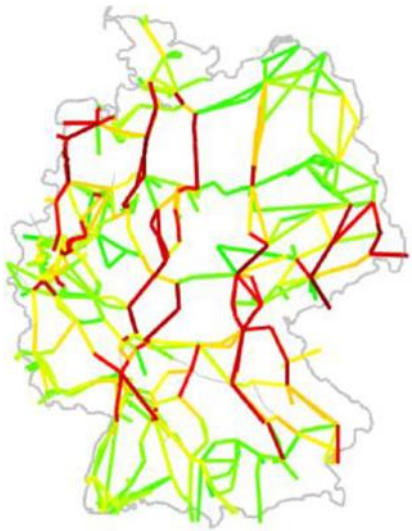

FIGURE 5 – GERMAN TRANSMISSION GRID BEFORE REDISPATCH
(SOURCE: BNETZA, GERMAN REGULATORY AUTHORITY, 2017)

After performing redispatch at transmission level, there are still some lines with more than 100% use of capacity already in the (n-0)-case (red bubbles in Figure 6). The goal is to reach always a line loading of less than 100% in the (n-1)-scenario to fulfil the (n-1)-criterion. Including RES connected to the distribution grids in the redispatch process, would increase the redispatch potential to achieve a line loading in the transmission grid to be lower than 100% for the (n-1)-scenario.

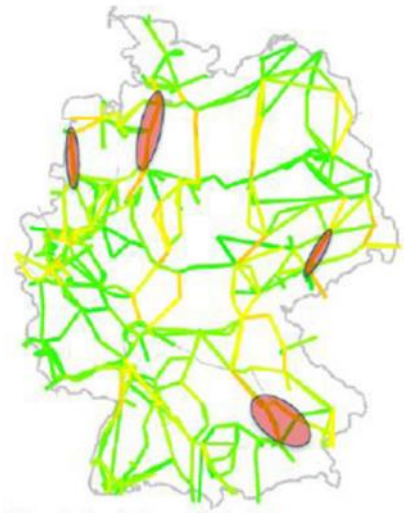

FIGURE 6– GERMAN TRANSMISSION GRID AFTER REDISPATCH
(SOURCE: BNETZA, GERMAN REGULATORY AUTHORITY, 2017)

Additionally, the increasing share of RES is leading to higher requirements for voltage control. An event from 24.10.2018 where around 1 GW of infeed was curtailed as an emergency measure in the HV grid of MITNETZ STROM because of voltage violation in the EHV grid caused by significant forecast deviation stipulates these increasing requirements. Reactive power flexibility could not be used due to lack of knowledge of reactive power flexibility potential in distribution grid. Therefore, such a high amount of active power needed to be curtailed. The system for enabling reactive power flexibility provision to the TSO from the distribution grid connected flexibility resources has been developed in EU-SysFlex German demonstration within the WP6.

Internal Driver: Cost efficiency

The German Demonstration has shown how to use all possible generator flexibilities in the DSO grid in order to solve grid congestions in the TSO and DSO grid in the most cost-efficient way. For cost-efficiency, the amount of needed flexibilities can be reduced if flexibilities are close to where the congestion is occurring. Under today's regime for congestion management, the costs will increase, also caused by the needed balancing. The costs for congestion management in 2017 reached a new record of 1.4 billion € [4].

Reactive Power flexibilities for voltage control face the same technical problem, but today the amount needed is provided via the regulations in grid connection contracts between Generation Operator and System Operator, so that there are no flexibility costs. In the future, the needed amount could rise above the potential available via grid connection contracts. The use of flexibilities for voltage control will also be shown in the German Demonstration.

In summary, the main drivers considered in the German Demonstration are external drivers, namely the increased share of RES, especially volatile RES like wind, not located close to the demand sites and increasingly connected to the distribution grid, which leads to a structural change in the power system. That leads to higher requirements for congestion management and at the same time to a shortage of redispatch potential in the transmission grid. Uncoordinated measures of the TSO and DSO can lead to counteracting measures. Therefrom arise the technical needs of active and reactive power flexibilities for congestion management and voltage control as well as the

regulatory requirements for a cost-efficient process. To achieve a cost-efficient process, coordination is needed, that consider all constraints for TSO as well as for DSO.

2.2 GOALS OF THE DEMONSTRATION AND CONTRIBUTION TO WP6 AND PROJECT OBJECTIVES

The German demonstration was set up to estimate a possible flexibility range of reactive power at grid nodes at the DSO/TSO interface, and of active power at the unit level, in order to provide these as ancillary services to the TSO for congestion management and voltage control in the transmission grid. Furthermore, the demonstration disaggregates these estimated values at generating unit level to enable the addressing and use for distribution grid purposes. This estimation does not exist in today's grid operation in a forecasted way. The aim is to integrate RES connected to the distribution grid into the schedule-based process for congestion management and voltage control in the transmission grid while considering the interdependencies between active and reactive power flexibilities of these units.

One main research object was to estimate the future grid states based on grid simulations and improved forecasts as well as the interferences (e.g. restrictions, dependencies or disturbances due to load flow) in the meshed grid in order to foster a transparent coordination at the TSO/DSO interface. The demonstration is following a new approach. The new approach has considered the availability (including load and generation forecasts) and cost (today regulatory fixed compensation and, in the future, potentially bids from a flexibility market) of flexibility. In addition, the approach has considered the impact on the requested operating point in the network as a flexibility activation changes the technical sensitivities in the grid. This approach is to find the most efficient solutions concerning costs and impact when managing active and reactive power requests from the TSO, considering system stability and optimisation of the whole power system (both in the transmission and distribution grid).

The goal of the demonstration was to result in a more accurate estimation of the power network state and its predicted future states. With the knowledge of the power flow in the distribution network, a more realistic flexibility range of active and reactive power can be offered to the TSO. This will result in requests that are more accurate from the TSO leading to less corrective actions such as curtailment of the PV, which can lead to high costs due to the fact that currently a lot of PV units are not equipped to react to curtailment requests. The communication and coordination between TSO and DSO is improved due to direct insight for the TSO in the available flexibility ranges from the distribution grid. In Figure 7, the objectives of the German demonstration are presented and which SUC's (System Use Cases) contribute to the implementation:

- **Forecasting** generation and consumption connected to the HV grid;
- **Predicting** power flows in the HV grid, including possible power flows due to contracted capacities for frequency stability services which might be activated by the TSO;
- Taking into account all grid constraints due to security reasons in the distribution grid including flexibility activation for **congestion management** in the distribution grid;
- **Providing information** of the available flexibility potential of active power (day-ahead and continuous intraday update) and reactive power (intraday - up to 6 hours ahead expected) to the TSO;
- **Enabling the delivery** of flexibility services and the execution of the TSO's calls for flexibility.

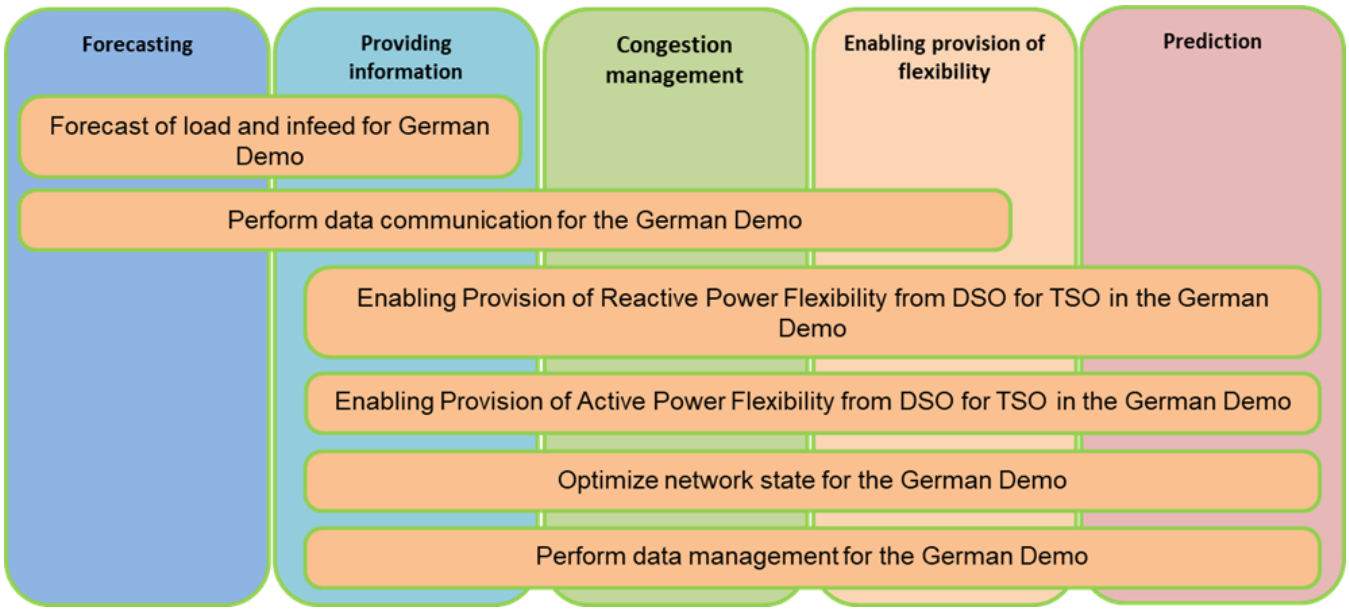

FIGURE 7 –OVERVIEW OF THE GOALS OF THE GERMAN DEMONSTRATION AND WHICH SUC'S CONTRIBUTE TO THE IMPLEMENTATION.

2.3 INNOVATION OF THE DEMONSTRATION

The innovation of the German Demonstration in general is including RES in congestion management by setting up a new and coordinated process for congestion management and developing an automated tool for voltage control and reactive power management. For those reasons, the integration of new and improved forecasts for RES generation and load are needed.

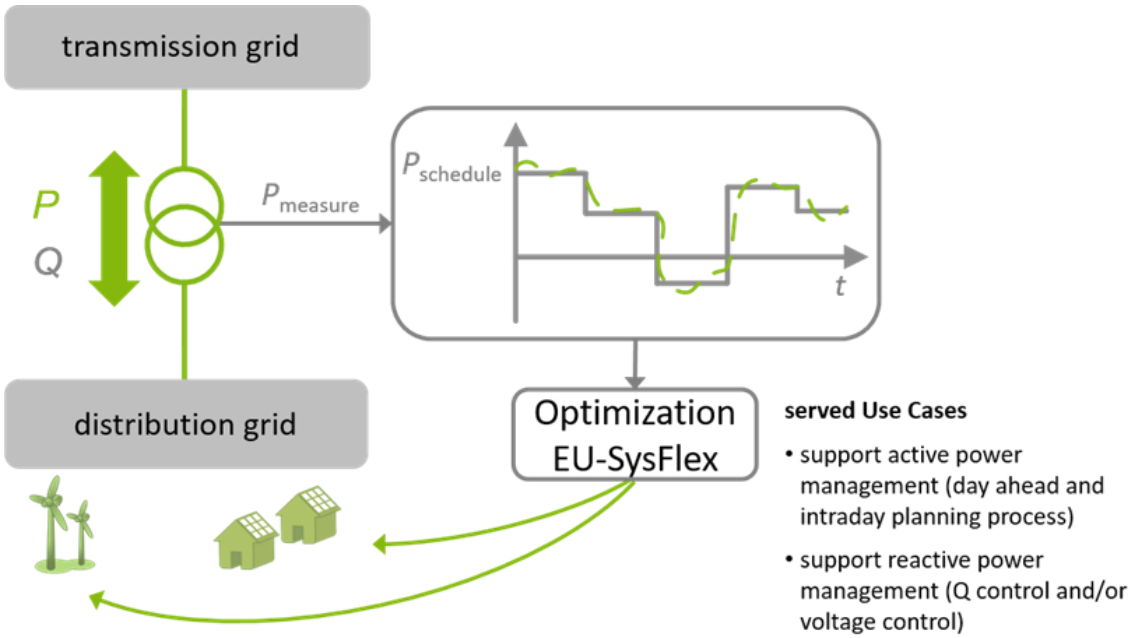

FIGURE 8 – OVERVIEW OF EU-SYSFLEX OPTIMISATION IN THE GERMAN DEMONSTRATION (SOURCE: ADAPTED FROM [8])

The innovation is furthermore reflected in the combined optimisation of active and reactive power as it is illustrated in Figure 8. The illustration shows that the active and reactive power provided from the distribution grid to the transmission grid is controlled and jointly optimised in the EU-SysFlex optimisation. Additionally, Figure 8 illustrates how the requirements for active and reactive power coming from the transmission grid are followed and how the requirements are broken down for individual plants included in the Demonstration.

2.4 LIMITATIONS

The use of flexibilities in the German Demonstration is subject to the regulations of RES. The settlement of innovative products cannot be implemented unless it fits into today's regulatory framework, but the technical feasibility can be shown. Due to this, the use of flexibilities from RES is settled as curtailment within today's regulations. In contrast to settlement, the technical process to integrate RES is innovative and developed within the demonstration.

2.5 EXPECTED RESULTS

The expected outcome of the German Demonstration is the enabling of flexibility services provision from DSO connected sources to the TSO, for the TSO's congestion management need due to line loadings and voltage limit violation. Figure 9 shows at which voltage levels these RES, providing flexibility, are connected and to where they are offered. It illustrates that in the German Demonstration flexibility resources from the 110 kV voltage level are offered to the transmission level and are additionally used in the 110 kV level itself. Furthermore, Figure 9 displays what scarcities these flexibilities solve. In the German Demonstration, the flexibilities are used as measures against voltage violations and congestions.

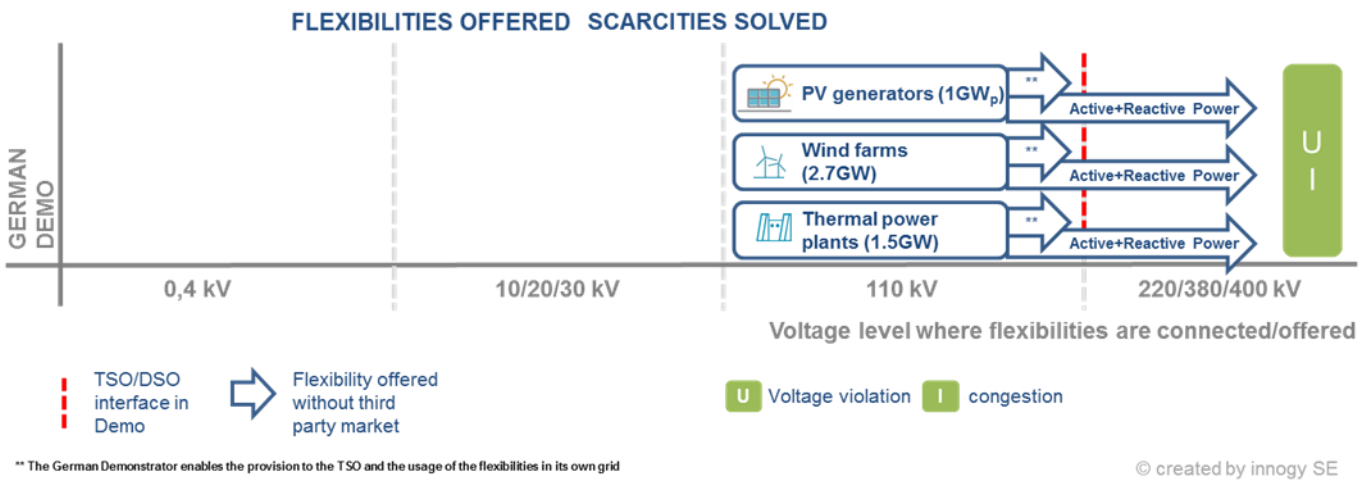

FIGURE 9 – FLEXIBILITIES OFFERED AND SCARCITIES SOLVED BY FLEXIBILITIES

The German Demonstration is developed to show a functional verification with real actions in field test for the developed process in active and reactive power management. The foreseen development results in a prototype status ready to implement in real operating processes. That includes the proof of concept of an efficient process with an increase of flexibilities, which can be used at the transmission grid as well as a loss optimised distribution grid. The increase of the use of flexibilities implies a cost-efficient use of active and reactive power for ensuring the maximum feed-in of RES.

The German Demonstration shows as well the feasibility of a fully automated process for a combined grid optimisation in active and reactive power flow, based on an accurate forecasting. Another result of the German Demonstration is the proof of concept of the developed coordination process between TSO and DSO for redispatch. Developing innovative settlement and proof of concept is in scope of the German Demonstration, whereas pointing out the limitations of today's settlement is outside of the scope. The same goes for market frameworks for using the flexibilities, because market framework and settlement are mutually dependent and are based on regulatory framework.

3. EU-SYSFLEX DEVELOPMENTS WITHIN THE DEMONSTRATION

The innovation in the German Demonstration regarding active power management is the coordination between the TSO and the DSO within the automated process of schedule based congestion management. The innovative process is based on the existing one, using flexibilities of conventional resources in transmission grid, and is being broadened to integrate RES, connected to the distribution grid, in it. The main difference to the status quo process is the integration of the DSO in the whole process and not only in emergency measures close to real time. The process enabling the provision of active power from flexibilities in the distribution grid to the TSO for relieving congestion in the transmission grid is defined as follows:

First, congestions in the distribution grid are managed by the DSO, and then the remaining flexibility potentials of active power are offered to the TSO. The TSO calculates power flow in its network and requests the necessary flexibilities from the DSO for the German and the European redispatch process. In case of flexibility requests, the DSO breaks the flexibility call down on individual plants and gives the instructions to the appropriate plants for respective timetable changes. This day-ahead process is illustrated in Figure 10.

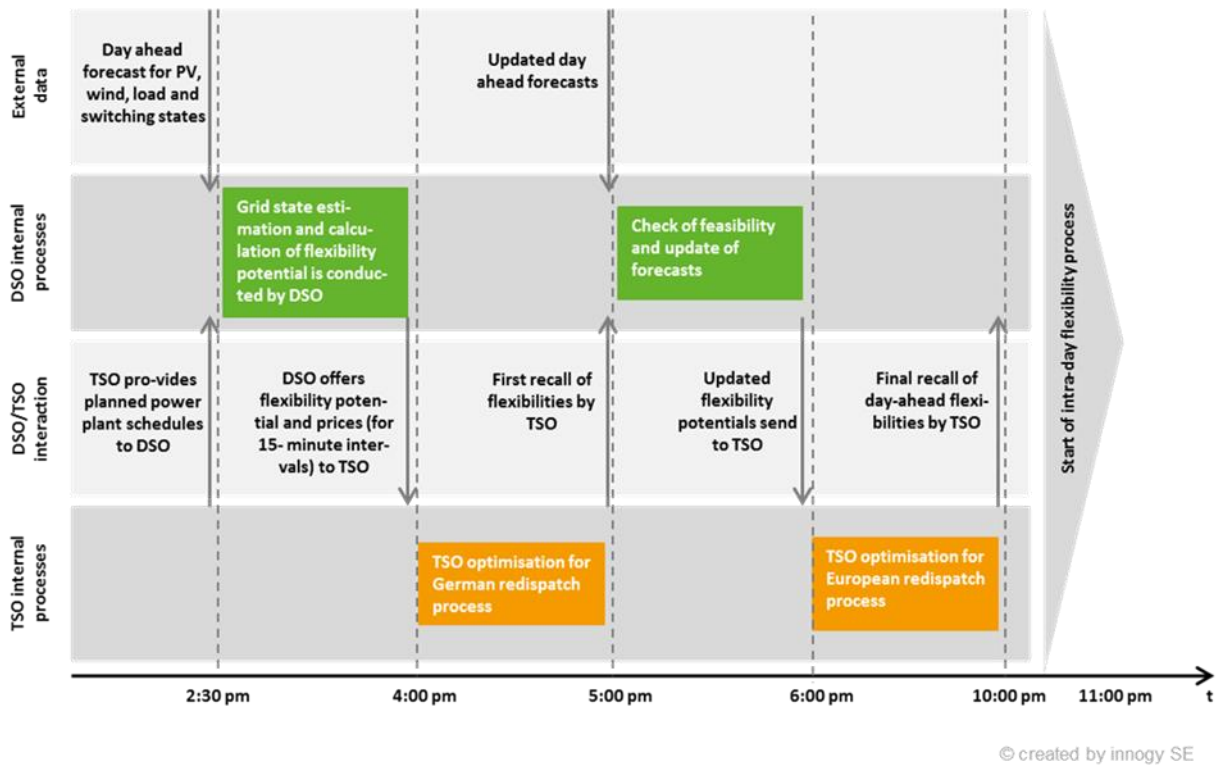

FIGURE 10 – DAY-AHEAD PROCESS FOR ACTIVE POWER FLEXIBILITIES

Due to forecast deviations, a continuous intraday process for active power flexibilities is set up in addition to the described day-ahead process. The intraday process is visualized in Figure 11.

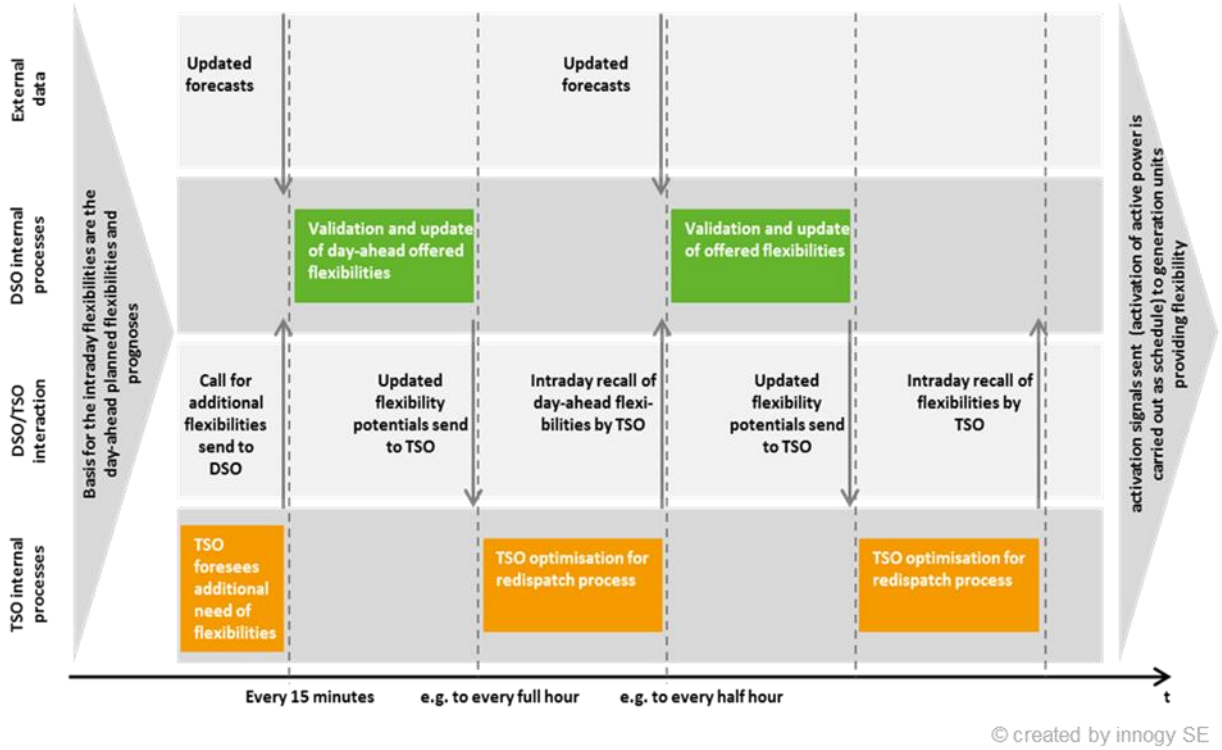

FIGURE 11 – INTRADAY PROCESS FOR ACTIVE POWER FLEXIBILITIES

The principle of the EU-SysFlex Demonstration is the same as one variant defined in PG FHWM (project group of TSO and DSOs to define how to coordinate frequency control and active power management) - with the difference that it is put into practice in EU-SysFlex. The German Demonstration therefore builds upon the results from the defined processes of this project group of TSO and DSOs and puts one process into practice to test it. Therefore, the needed functionalities will be defined and developed. The results of the field test will be evaluated to detect further development needed for an automated process. While preparing the field test and defining the data exchange, as described in chapter 3.1, new regulation schemes were discussed and the experience of these preparations could be brought into this discussion. As a result, the regulation in action since 01st October 2021 is in line with described congestion management approach of the German demonstration.

The innovation in the German demonstration regarding reactive power management is the set-up of an automated tool for dynamic voltage control and reactive power management. In today's voltage control actions, dynamic local voltage control in the distribution grid is not considered as flexibility for transmission grid. The demonstration has exactly the goal to show the feasibility of reactive power flexibilities from plants in the distribution grid as a service to the TSO.

For this, the DSO runs a combined optimisation for active and reactive power calculating the reactive power potentials, which can be offered to the TSO. As soon as the TSO foresees possible violations of voltage limits, flexibilities from the offered potential can be requested. The process for this is illustrated in Figure 12. The goal is to set up an automated process for this, which will be running in parallel at first, but is built to be running fully automated in the long term.

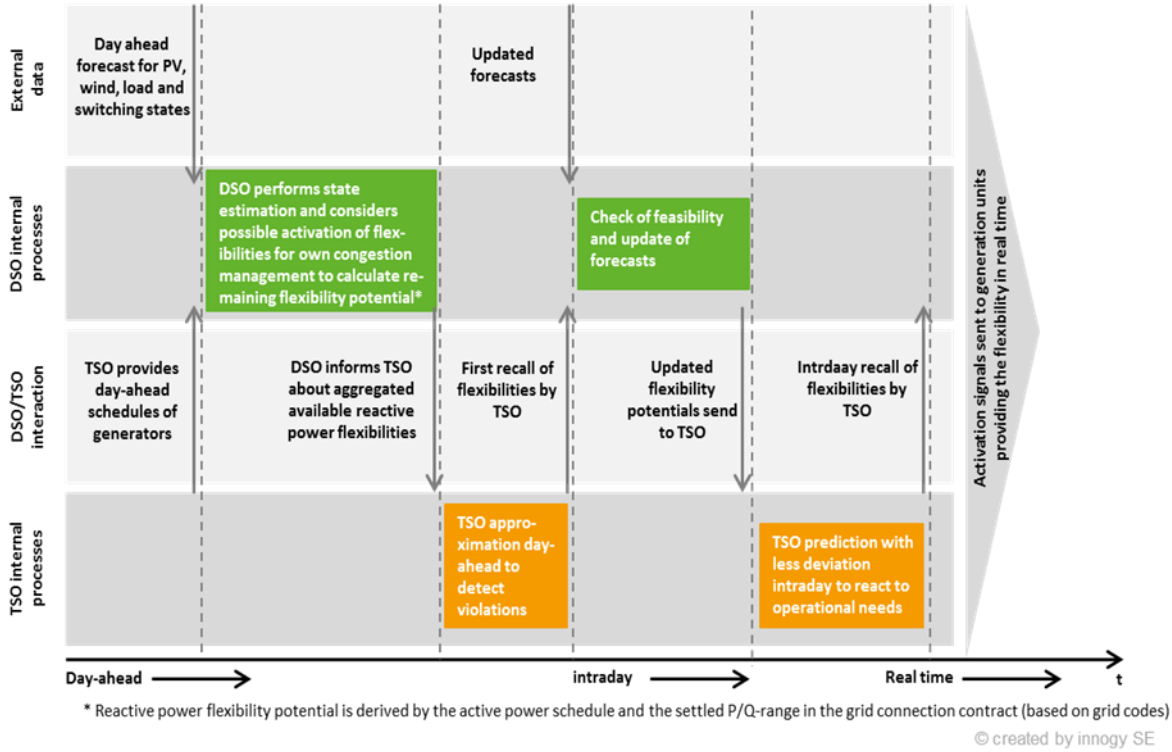

FIGURE 12 – PROCESS FOR REACTIVE POWER FLEXIBILITIES

3.1 OVERVIEW OF DATA HANDLING AND ICT INFRASTRUCTURE

In the German demonstration, the grid control centre's operating system sends Zip files via SCP (Secure Copy). The zip file contains four CIM files, one file per CGMES profile, namely:

- Equipment profile (EQ) for device information.
- Topology profile (TP) for grid topology information.
- Steady state hypothesis profile (SSH) for load flow simulation.
- State variable profile (SV) for measurement information.

Additional asset master data, like flexibility costs and protection parameters, are also sent.

The Software Platform validates and captures the CIM files to transfer their contents to a database (PostGresSQL). Other applications (e.g., calculation of the operating schedule) have access to the data via a REST (REpresentational State Transfer, software architecture used for Web services) interface. The data for the forecast (.csv files) are sent in the same way from the DSO to the Software Platform. The operating schedules are displayed by the Software Platform, in an XML file defined by the grid control centre software manufacturer and sent back to the grid control centre via the same route.

The communication between DSO and TSO is set up as a secure connection between the two grid control centres. The standardised protocol of IEC 60870-6-TASE.2 enables the permanent exchange of data and information. If there is new information, it will be transmitted. In addition, CIM data is transferred within the GLDPM process.

Addressing the field assets with new set points is performed through the protocol of IEC60870-5-101 with a customised data model.

The DSO grid control centre sends measurements from the grid nodes via FTPS (file transfer protocol secure) to the Forecast Providers packed as a .zip file. The .zip file contains four CIM files, one file per CGMES profile, namely:

- Equipment profile (EQ) for device information.
- Topology profile (TP) for grid topology information.
- Steady state hypothesis profile (SSH) for load flow simulation.
- State variable profile (SV) for measurement information.

Furthermore, the DSO sends meta information about geographic location and installed capacity to the Forecast-Provider via FTPS (File Transfer Protocol Secure). These data are only sent if changes occur.

FTPS was chosen because it guarantees secure encrypted traffic that is difficult to infiltrate with malicious code. The FTPS server is located at the Forecast-Provider and is administered by him.

The numerical weather prediction (NWP) provider delivers weather forecast to the FTP (file transfer protocol) Server located at the Forecast-Provider or makes the data available on its own FTP server. FTP is used by default by the providers because the data is not highly classified, but the data volume is quite large with several GB per delivery. By using FTP it is taken care that no excessive data overhead and efforts for encryption arise.

Error! Reference source not found. and Table 1 summarize, for each pair of systems, the information exchanged in the German demonstration, what kind of systems communicate, the protocol used for the data transfer and the reason for choosing that protocol. In Figure 13, the plain arrows show communication channels used and implemented in the demonstration. They are tagged with the data models (e.g. CIM) and the communication protocols (e.g. IEC 60870-5-101) used for the exchanges. The dotted arrow represents communication that is relevant for the system but are out of scope of the demonstration.

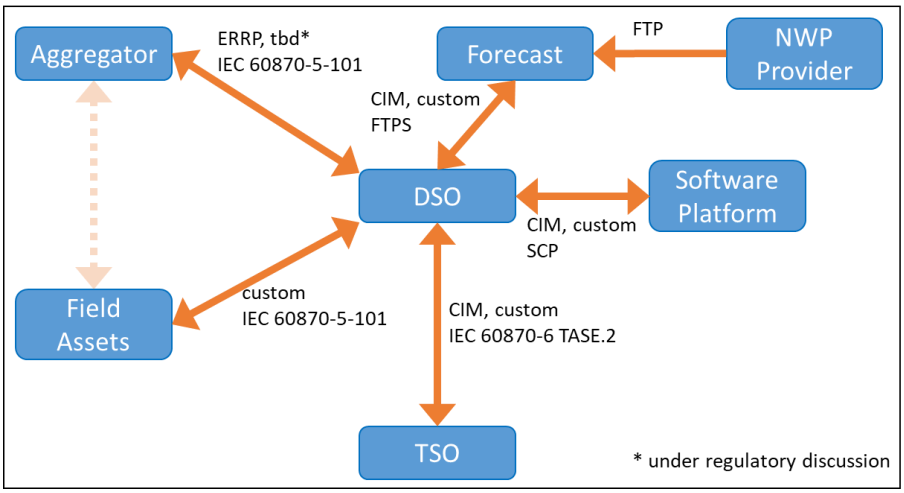

FIGURE 13 – SIMPLIFIED COMMUNICATION IN THE GERMAN DEMONSTRATION

TABLE 1 – COMMUNICATION LAYER SUMMARY FOR THE GERMAN DEMONSTRATION

SYSTEM 1	SYSTEM 2	PROTOCOL	REASON
DSO	FIELD ASSETS	IEC 60870-5-101	Historical, security
DSO	AGGREGATOR	Regulation under discussion	Historical
AGGREGATOR	DSO	IEC 60870-5-101	Security
DSO	SOFTWARE PLATFORM	SCP	Security
SOFTWARE PLATFORM	DSO	SCP	Security
DSO	FORECAST	FTPS	Security
FORECAST	DSO	FTPS	Security
TSO	DSO	IEC 60870-6 TASE.2	Security
DSO	TSO	IEC 60870-6 TASE.2, CIM	Security
NWP PROVIDER	FORECAST	FTP	System given by Provider

The process wherein the data exchange is embedded is as follows:

- In the German Demonstration, the DER sends the schedule and flexibility offers to the DSO, which selects flexibilities for its own use and aggregates the potential for the TSO. The TSO then selects aggregated flexibilities for the use on its own grid. The DSO verifies the feasibility of the TSO's requests, segregates and sends the signal to the DER aggregator, which adapts the active power of its asset. Active power in the German Demonstration is used for congestion management and in very few cases for voltage control.

- In the German Demonstration, the DER sends active power schedules to the DSO, which determines the units' reactive power potential based on their grid connection contract. The DSO selects the flexibilities for its own use and aggregates the potential at the grid connection point to the TSO for reactive power. The TSO determines its reactive power demand and sends this information to the DSO. The DSO checks the feasibility and segregates in order to send reactive power set points to the DER.

- As detailed above, the TSO sends a request directly to the DSO informing about what kind of flexibilities are needed. It is then the DSO's responsibility to fulfil this request. The TSO is therefore not directly controlling any assets, devices and generation units connected to the distribution networks, since this may create problems such as congestion in the distribution grid. The DSOs take care that the TSO requests are fulfilled but in such a way that no additional congestion is created in the distribution grid guaranteeing a congestion free, secure and reliable distribution system operation.

3.2 DESCRIPTION OF FUNCTIONALITIES

The following chapter is giving an overview of the most important functionalities of tools implemented in the demo to realise the use cases defined for the demo. The System Use Cases (SUCs) and the associated functionalities are shown in Figure 14.

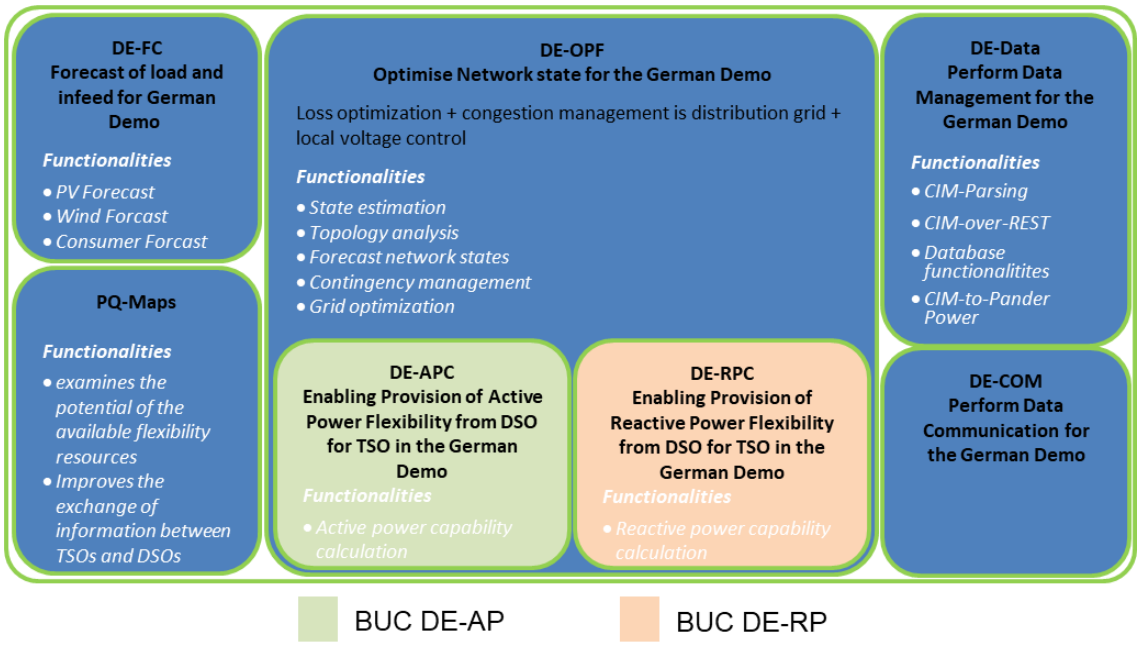

FIGURE 14 – MAPPING OF SUCS AND FUNCTIONALITIES

The following description gives a short explanation to overview the main tools.

- **Observability and forecasting tools** (see Deliverable D6.2 [14])

  Existing forecasting and observability tools will be adapted in the context of the different demonstrations and evolved to meet the specific needs. With the help of these tools, the operation of the system can be substantially improved with forecasts of variable resources, of the market situation, the network needs and of how the distributed resources would behave with or without price and control signals. This leads also to a higher observability of the system and hence more accurate network states.

- **State Estimation**

  For the network with grid measurement available, the classical WLS grid estimation is performed. The tool is developed and available in the open-source tool pandapower. The goal of the state estimation is to verify the correctness of the interpretation of the grid modelling and improve the accuracy of grid status.

- **Optimisation tool IEE.NetOpt** (see Deliverable D6.5 [16]):

  Within the scope of the German demonstration, the already existing optimisation tool of partner Fraunhofer IEE was modified to achieve the goals of the project. New functionalities have been added to the core algorithm for exploiting this tool within the EU-SysFlex project:

  - The former 'static' optimisation program was transferred into a real-time optimisation tool called IEE.NetOpt, capable to optimise presently existing networks with a changing number of e.g. nodes, lines and generators. Thus, grid specific objective functions are generated automatically based on the individual grid components
  - Various new constraints like (n-1) security, load angle restrictions based on power flow directions have been added. Additional limitations could be implemented easily.
  - Several operation modes of the flexible units were implemented as new constraints

- Taking into account these adaptions, IEE.NetOpt is able to calculate different, optimised set points relating the TSO-DSO connection point/points like active or reactive power flexibilities as well as individual set points for the controllable flexible units in the DSO grid. Even in case a desired request (set point) relating the TSO-DSO connection point/points cannot be realized, the optimisation algorithm of IEE.NetOpt ensures optimal system operation. To do so, several hard constraints are moved to the objective function to ensure solvability of the given problem at any time.

The resulting optimisation tool is capable to carry out the functionalities described in the SUCs presented in D6.1 [5], adequately fitting in the business process defined for the German demonstration. Simulations of network scenarios with different shares of controllable resources allowed testing the capabilities of the optimisation tool. They lead to accurate and realistic results and returned valuable knowledge for the field tests [6].

Currently, the optimisation tool considers only a single set point like controlling the active power magnitude at a single grid connection point. In case of corresponding demands of the system operator, the objective function of the optimisation could be modified in future to take into account multiple demands.

- **Optimation tool PQ-Maps** (see Deliverable D6.5 [16])

Aiming to fulfil one of the main goals of the German Demonstration, enable a fast and reliable communication between TSO and DSO through optimisation mechanisms, the PQ-Maps tool [17] effectiveness has been assessed by applying it to a real 110 kV distribution network operated by MITNETZ STROM. The demonstration activities were specifically focused in three EHV/HV substations (Marke, Klostermansfeld and Lauchstädt) since their interconnection through both the EHV and HV sides allows to properly analyse the PQ-Maps novelties. The algorithm capabilities to provide direct insights for the TSO concerning the available flexibility margins at the interfaces with the DSO were inherited from the FP7 evolvDSO and were enhanced in the course of H2020 EU-SyFlex so that meshed connections would not become an obstacle. Therefore, the demonstration tests will be centred in highlighting not only the flexibility ranges estimation, but also how they are redistributed throughout the different TSO-DSO interconnections.

Since such ability is dependent on the knowledge of how the transmission network behaves, the German demonstration will be used as a real environment to test the data-driven building process of transmission grid equivalents. In the absence of the real transmission network, whose availability would enable a more straightforward assessment of the equivalent model reliability, the demonstration tests will use distance metrics to compare the PQ-Maps operating points with and without the equivalent (i.e. no knowledge of transmission network behaviour). By doing so, it will be possible to estimate the errors that arise when neglecting the impact of the transmission grid on the power flow distribution over the different TSO-DSO interfaces. Although for the majority of the German demonstration KPI's defined in [7] it is not possible to establish a quantifiable link with the PQ-Maps, there is a correlation that cannot be neglected. Particularly in the KPIs associated with meeting TSO needs, the higher observability promoted by the PQ-Maps works as a facilitator to fulfil such objectives. Additionally, the computational time associated with the algorithm will also impact

on the time-related KPI's defined in [7]. The final results – the PQ-Maps in each EHV/HV substation – will be presented to the user through a dedicated GUI.

Besides these main tools, several supporting tools were created to ensure robust and reliable function. To guarantee operation of all tools, an architecture with needed interfaces were developed. This communication and data usage of tools is described in deliverable D6.4 [6].

In preparation of the field test, a quasi-static grid simulator was developed as shown in Figure 15. The goal is to model and simulate different network states, to consider the impacts to the local grid from offering flexibility from DERs. The DER and Tap Changer modelling is supported in the simulation framework. The grid simulator can be connected to the laboratory demonstration in the way that, the effect of applying the optimised set point of the demonstration can be directly simulated and verified. Thus, it is ideal tool for the development and test phase of the German demonstration. Further development regarding the integration of a high-performance power flow solver is still undergoing, so that in the future the uncertainty can be directly considered in the online simulation.

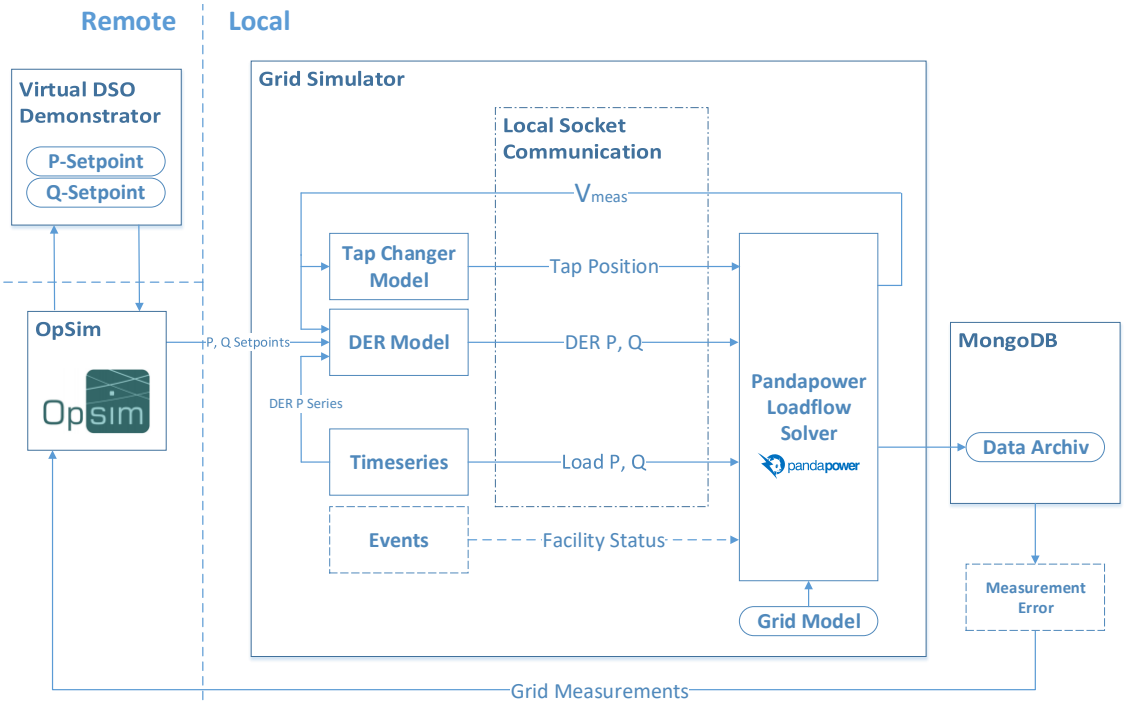

FIGURE 15 – SCHEMATICS OF GRID SIMULATION IN GERMAN DEMONSTRATION

4. FIELD TEST

This chapter describes how the tools and function were tested and show the results achieved. In the beginning, the analysis of accuracy of forecast is described and it is followed by the analysis of state estimation accuracy. The accuracies of forecast and state estimation are base for the accuracy of the whole process. As the optimisation mathematically processes these input data, the overall accuracy is strongly dependent on the input accuracy. The whole chain of tools and functionalities represent the Decision Support Tool in congestion management and voltage control for grid control centre operator. To evaluate the developed Decision Support Tool, the impact of measurement inaccuracies on the execution of proposed set points is described as well as the comparison to existing congestion management. The influence of data availability is shown with the results of the PQ-Maps tool. To conclude this chapter the analysis of process timing to meet the developed processes is described. Additional to the main function of the Decision Support Tool, the optimisation targets the minimisation of the grid losses. Therefore, the analysis of grid losses is included in this chapter.

4.1 PV /WIND AND CONSUMER FORECAST

As part of the EU-SysFlex German demonstrator, a forecasting system was implemented which forecasts the individual generators and loads on the busbars or transformers at the MV/HV level for a period of up to a maximum of 48 hours into the following day. In that respect, it takes into account the configuration of the underlying MV grid. A detailed description of the complete forecasting system can be found in Deliverable 6.2 of the EU-SysFlex project [14].

In this chapter, the forecasting system is briefly recapitulated, and the current status is described. This is followed by the evaluation of the forecast quality for the different generators and loads, which includes the wind power and PV forecast and the vertical loads. Followed by the briefly discussion of the Key Performance Indicators in relation to the forecasting system in EU-SysFlex.

4.1.1 GENERATION FORECAST

Due to the need to dynamically allocate the generators to the busbars, depending on the current switching of the substations, a multi-track approach was chosen for the forecasting system. The wind power and PV forecasts were designed as so-called physical models. The vertical power flow forecast on the other hand is based on a machine learning approach. With this combined approach, the mixed measurements at the busbars could be forecasted in a satisfying way. The physical models simulate the physical processes in the generator in a simplified way, which can also be done using generalised power curves. To further improve the PV and wind models, two statistical approaches were included in a second step. For the PV correction, the time series of direct-feeding parks were used to enable a uniform correction function across all parks, which can then also be used for the mixed feeders.

For the vertical power flow forecasts a Long-Short Term Memory (LSTM) was used, which is described in D6.2 [14]. Due to the challenges posed by a dynamic grid, the machine learning approach first used was extended to include a new approach that updates the previously trained LSTM models. This update approach is presented, investigated

and compared to three different baseline models in [9]. This paper describes the main work for the vertical power flow forecast and was created as part of the EU-SysFlex project. In this chapter the main contents of the paper is summarized, so that further descriptive details can be found there. Furthermore, some text parts and figures are copied from this paper.

For the updated process, the LSTM model is retrained regularly as soon as a sufficient amount of new measurements are available. By incorporating the new measurements, the model can detect changes in the characteristics of the transformer and thus improve the forecast.

Evaluation of the forecast quality of the Wind and PV power forecast

In this section, the quality of the Wind and PV power forecast is discussed. This is done based on historical data, as a more detailed breakdown of the time series by busbar. It is possible here due to the availability of the corresponding data. So, individual time series could be selected where only one generator type and no loads are present.

At the end, it allows 144 wind farms and 35 PV parks to be included in the evaluation. The year 2019 has been used as the evaluation period and the second half of 2018 will then still be taken in part for the calibration of the models. The forecast is based on the Cosmo-D2 numerical weather prediction (NWP) model of the German Weather Service (DWD). In the demonstration system, this has been replaced by the newer, improved ICON-D2 model, which was unfortunately not operational until February 2021. For evaluation of the new models benefit, the time range was too short.

The forecasting system is based on a chain where, at the beginning, the numerical weather prediction (NWP) on a grid provides the variables to the module (radiation, wind, etc) that performs the transformation into energy generation representing values. Thus, for each grid point a normalised power value of a standard park is calculated. The power value is then interpolated from the grid to the park coordinates and scaled with the nominal power of the park. Afterwards the parks are mapped to the busbars via an allocation matrix. For the different application purposes, the transformation module is exchanged and the input data from the NWP model is adapted.

PV FORECAST

This section compares the two forecasting approaches used for the PV forecast. At the beginning, a purely physical approach for the transformation from radiation to power was used, which, however, had some deficits. This was then significantly improved in the second approach, where a statistical correction was added to the system.

Basemodel

The first version used for the transformation module a PV forecast model from the Fraunhofer Solar Prediction System (SPS) [10], as also described in Deliverable 6.2 [14].

Improved Model with Model Output Statistics

After examining the time series, it became apparent that the rise in the morning and the fall in the evening were too weak in the forecast. This effect was evident at all locations and could not be compensated for in the model by changing the angle of incidence. In addition, the model systematically underestimated the nominal power of the

PV systems given in the master data from the DSO. To improve the forecast quality and correct this behaviour, an approach was chosen that can be used after optimisation across all sites, as it is difficult to optimise busbars or transformer inputs separately where a mixed feed-in is present.

Therefore, a post-processing with a model output statistics MOS was chosen over all sites, in which the model output was post-corrected. As an approach, a non-linear function consisting of a linear and a logarithmic component was chosen and trained on measurement data, where only PV feed-in was present. For this purpose, 35 PV parks were selected and the model was fitted with data from the period July to December 2018.

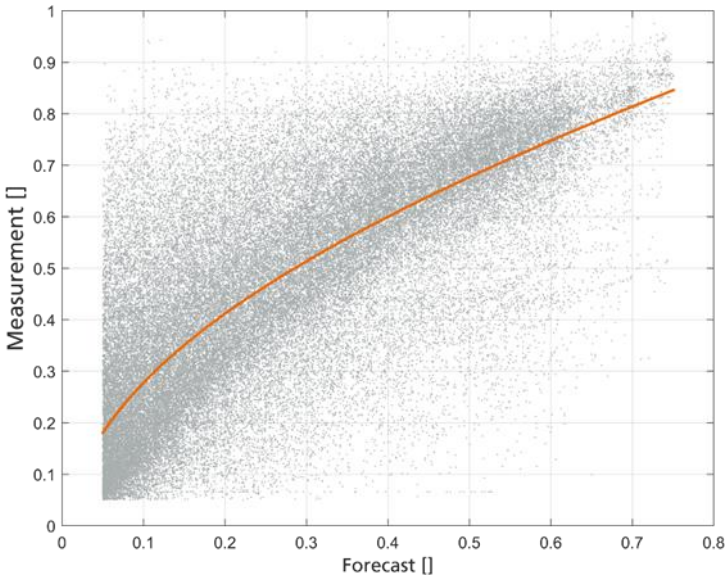

FIGURE 16 – MEASURED VALUES PLOTTED VERSUS THE FORECAST. THE FIT FOR THE MOS IS SHOWN AS ORANGE LINE.

The resulting fit on the training data can be seen in Figure 16. It shows that it can reproduce the statistics well, even if it sets the correction a bit too high for low outputs and slightly too low for high outputs. An example of a forecast for the current day is shown in Figure 17. You can see nicely how the previous forecast underestimates the measurement, but after correction is well in the middle of the fluctuations. The local fluctuations, probably due to individual cloud fields, could not predicted by the forecast model. The cause here is to be seen in the weather model, which is often unable to reproduce small-scale cloud formations accurately enough in a spatial resolution of 2.2 km. The morning and evening gradients also fit better now, even if they are a little overcorrected.

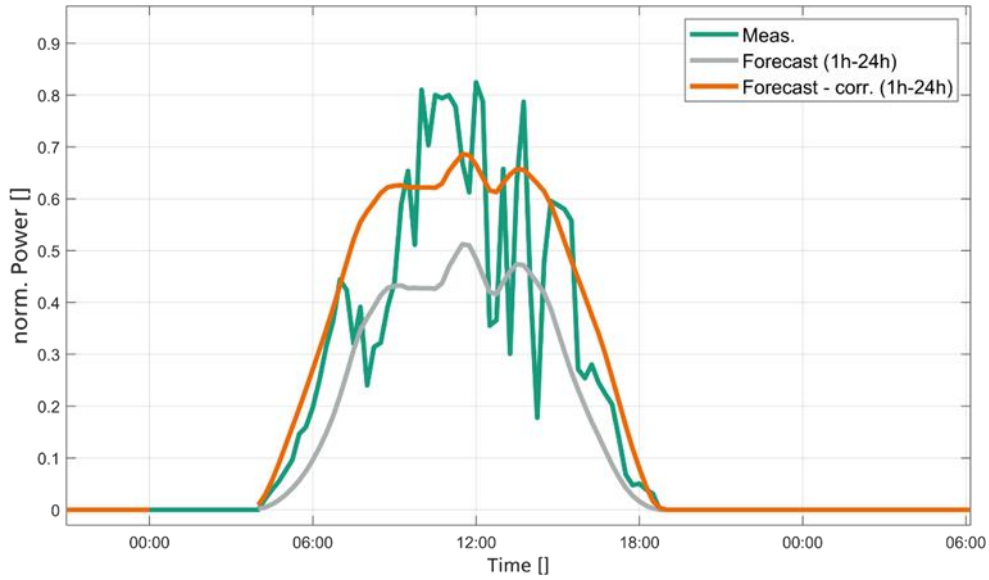

FIGURE 17 – EXAMPLE OF A DAILY COURSE BEFORE AND AFTER THE CORRECTION OF THE STATISTICS. THE GREEN LINE SHOWS THE MEASUREMENT AT THE BUSBAR, THE GREY ONE IS THE BASIC FORECAST AND THE ORANGE ONE THE CORRECTED FORECAST.

Comparison of the basic system with the extended version

The basic version is compared here with the calibrated version of the forecast for the intra-day and the day-ahead forecast. For the intra-day, the lead-time range of 3 to 6 hours is used, whereby the currently available forecast run of the weather model was always taken as the basis. For the day-ahead forecast, the available forecast from five o'clock in the morning (UTC), for the entire next day, was used. The Root Mean Square Error (RMSE), which was normalised with the specified nominal power of the wind farm (nRMSE), and the bias were used as error measures. In order to consider only the relevant time range of the forecast, the night hours were excluded.

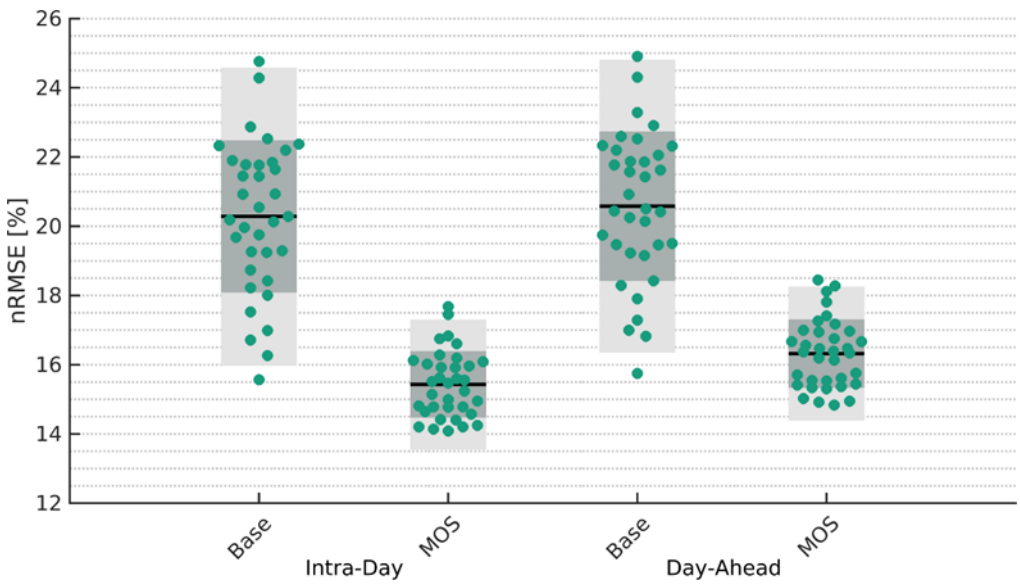

FIGURE 18 – UNIVARIATE SCATTERPLOT FOR THE PV PARKS. THE NRMSE OF THE SINGLE PARKS CAN BE SEEN TOGETHER WITH THE BOX-PLOTS IN THE BACKGROUND. ON THE LEFT SIDE THE RESULTS FOR THE INTRA-DAY FORECASTS ARE SHOWN AND ON THE RIGHT THE DAY-AHEAD FORECASTS.

The results of the evaluation are presented as two graphs, one for the nRMSE and one for the bias. The error values of the individual parks are shown as a univariate scatterplot, which is backed by a boxplot with a median line.
The baseline approach showed a quite poor result with an average nRMSE of 20.3% (see Figure 18). After applying the statistical correction, the values improved to an average nRMSE of 15.4%. This is quite reasonable. A very good effect is that the distribution of nRMSE values has narrowed greatly and even the poor PV-parks only go up to a maximum of 18% in the Intra-Day forecast. A similarly strong effect can be seen in the Day-Ahead forecast. Here, too, there is a considerable improvement and a sharpening of the distribution.

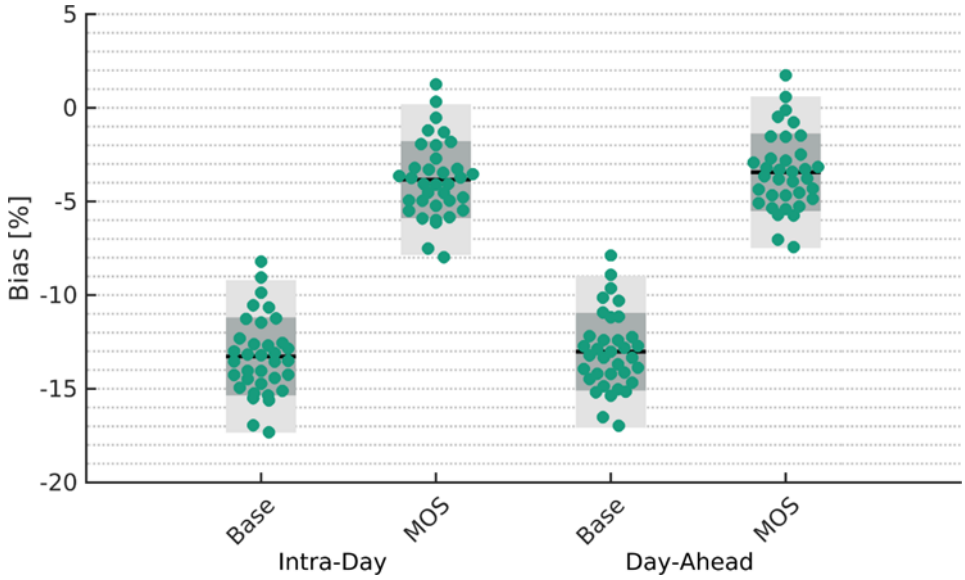

FIGURE 19 – UNIVARIATE SCATTERPLOT FOR THE PV PARKS.
THE BIAS OF THE SINGLE PARKS CAN BE SEEN TOGETHER WITH THE BOX-PLOTS IN THE BACKGROUND. ON THE LEFT SIDE THE RESULTS FOR THE INTRA-DAY FORECASTS ARE SHOWN AND ON THE RIGHT THE DAY-AHEAD FORECASTS.

In terms of bias, which is significantly reduced by the MOS (see Figure 19). The very high values are still not beneficial, but they are within a good range. In this case, the shape of the distribution is not changed much, but only shifted towards lower values by the post-processing.

WIND POWER

For the Wind power forecast, the standard chain was used as described in the introduction of the section. The difference against PV are the input parameters from the NWP model and the conversion from wind into power, which was carried out using a universal power curve in the baseline approach. In order to achieve a further improvement, a new universal power curve was calculated in the second approach, based on the data sets of the investigated wind farms

Baseline

In the baseline model, a universal power curve from the TradeWind project [11] was used to transform wind forecasts into power values.

Improved Power Curve

To improve the forecast, the standard power curve was adapted to the measured data set of the wind parks. Three approaches were tested to fit the power curve:

- The first, a fitting procedure based on a copula transformation.
- The second uses the maximum of a 2-dimensional distribution of the power curve to get the path of the curve.
- The third one is a simple binning.

As input data, the combined time series of wind and power from 144 wind parks were used for the fitting procedure. All three fitting algorithm were compared to each other and at the end the simple binning, as the best one, was used to create the adapted power curve.

Comparison of the basic system with the extended version

The wind forecasts are evaluated with regard to the nRMSE and the bias as described in the PV section. These evaluations were done for the Intra-Day and the Day-Ahead forecast separately. Corresponding to the evaluation of the PV parks, the RMSE and the bias of the wind parks are presented as univariate scatterplots. The mean nRMSE across all wind farms is 15.2% after applying the improved power curve, as can be seen in Figure 20. Compared to the basic version, it has only improved slightly. The nRMSE of the poorer wind farms can be improved in this way and thus the error distribution can be made slightly narrower.

In general, a mean error of 15% for the individual network nodes is already a good value for a forecast based on only one weather model and for which no calibration to the individual wind farm has taken place. The majority of wind farms are grouped around this value and in relation to the median in the graph, which is also around 15%, half of the wind farms are well below this value. In the subsequent day-ahead forecast, the nRMSE of the poorer wind farms are also reduced, but on average the nRMSE across the wind farms increases slightly.

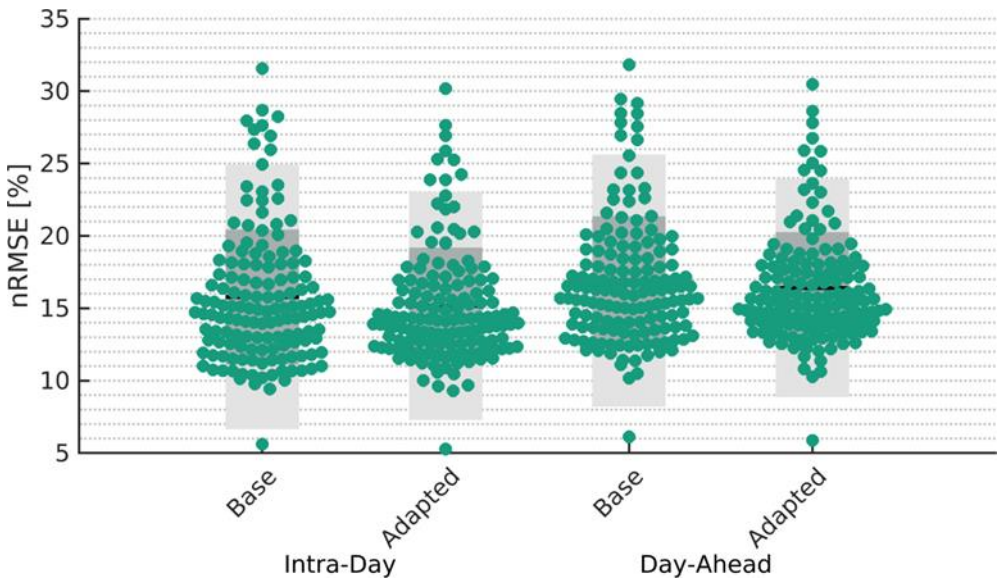

FIGURE 20 – UNIVARIATE SCATTERPLOT FOR THE RMSE OF THE WINDPOWER FORECAST.
ON THE LEFT SIDE THE INTRA-DAY FORECAST WITH THE BASE VERSION AND THE EXTENDED VERSION CAN BE SEEN, ON THE RIGHT THE CORRESPONDING DAY-AHEAD FORECAST.

With the bias (see Figure 21), one sees a shift in the distribution of the bias towards zero on average by applying the fitted power curve. This effect is visible for both the intra-day and the day-ahead forecast. A narrower distribution would have been desirable here, but could not be achieved with this approach.

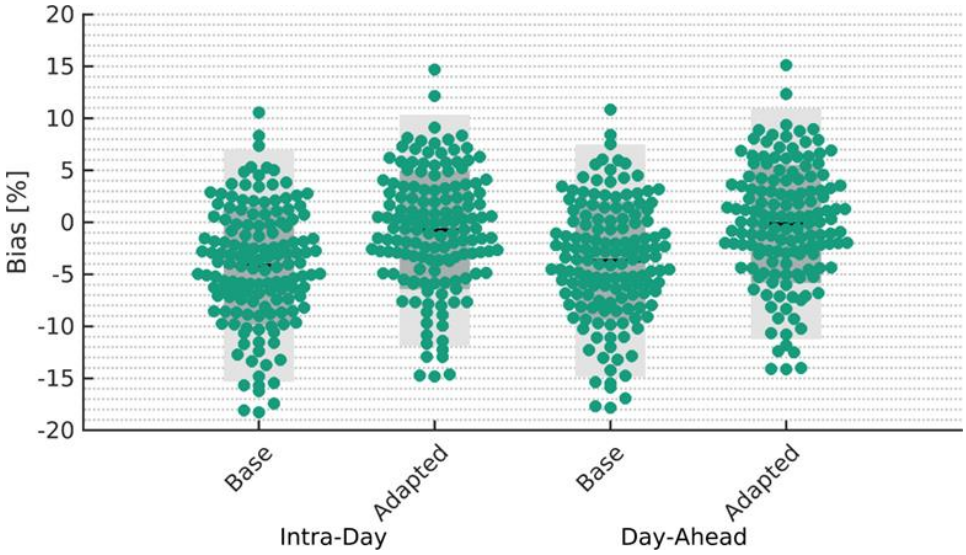

FIGURE 21 – UNIVARIATE SCATTERPLOT FOR THE WINDPOWER FORECAST BIAS FOR THE INTRA-DAY AND DAY-AHEAD FORECAST.

KPI´s and Conclusion

For the forecast demonstration of the wind and PV forecast, three KPIs can be seen as relevant:

- Quality of Forecast – Intraday: Evaluation of the forecast quality.
- Quality of Forecast - Day Ahead: Evaluation of the forecast quality.
- Process Duration: Processing duration of the forecast, e.g. the time span of wall clock time and the delivery time of the forecast to the DSO.

In the following, the forecast quality is evaluated and then the processing time of the forecast chain is discussed.

Quality of the Intraday and Day-Ahead forecast

As described in the previous section on the wind and PV forecast, the PV forecast was significantly improved by post-processing. This can be seen very well in the reduction of nRMSE, as well as a massive reduction of the bias. The wind forecast already showed a respectable quality at the beginning and could experience a slight improvement of the nRMSE in the intraday area with an adjusted power curve.

In the wind forecast, the mean bias was almost completely eliminated with the adjusted power curve. The results are summarised in Table 2 for the nRMSE and in Table 3 for the bias.

TABLE 2 – OVERVIEW OF THE ACHIEVED NRMSE VALUES WITH THE BASELINE AND THE IMPROVED FORECAST.

nRMSE	Intra-Day		Day-Ahead	
	Base	Improved	Base	Improved
PV	20.3%	15.4%	20.6%	16.3%
Wind	15.8%	15.2%	16.1%	16.3%

TABLE 3 – OVERVIEW OF THE ACHIEVED BIAS VALUES WITH THE BASELINE AND THE IMPROVED FORECAST.

Bias	Intra-Day		Day-Ahead	
	Base	Improved	Base	Improved
PV	-13.3%	-3.8%	-13.0 %	-3.4%
Wind	-4.2%	0.8%	-3.7%	-0.2%

PROCESS DURATION

The forecast chain consists of several individual modules, which are responsible for converting data, generating forecasts for wind and PV, combining forecasts from different forecast runs, exporting and uploading them to the target server. The conversion includes the import of the complete weather fields from the NWP delivery, which are available in GRIB format, and the conversion of CIM xml-files with the existing measured values. The forecast modules are then the two for wind and PV and for each processing line a combination- and export/upload-module (the functionality is combined in one module). The PV and wind lines can be executed in parallel, which can be seen very nicely in the flow chart (see Figure 22). And the extraction of the NWP, which only takes place every three hours and is not as time-critical in terms of its timeliness can be handled complete separately.

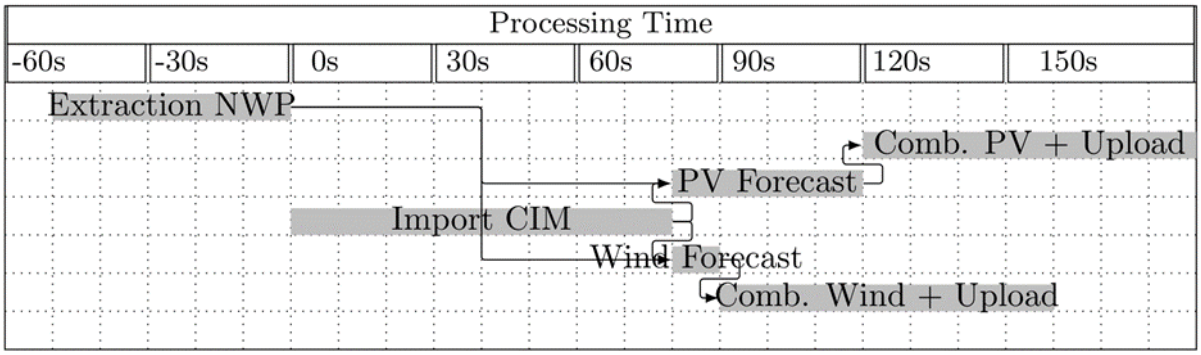

FIGURE 22 – TIME DIAGRAM OF THE PROCESSES AND CALLS OF THE INDIVIDUAL MODULES IN THE WIND AND PV FORECAST CHAIN. EACH GRID CELL CORRESPONDS TO 10 SECONDS. THE START TIME IS RELATED TO THE WALL CLOCK TIME WHEN THE FORECASTING SYSTEM STARTS CALCULATING.

If one looks at the time diagram, the longest process chain is the PV forecast with 3 minutes 10 seconds the value for the processing time is very close to the targeted three minutes for the entire forecast chain. Of the 3 minutes, 1 minute and 50 seconds fall on the actual PV forecasts for 17710 grid cells interpolated to 10368 PV parks, a really good value. The processing for the wind forecast branch needs 1 minute and 20 seconds for 558 wind parks, which is also quite good in time. Unfortunately, much of the valuable time is used for retrieving and importing the CIM data. Here, at the moment, no potential for any optimisation can be seen. In general, a very good result was achieved.

CONCLUSION

A demonstration system for the prediction of wind and PV power could be built, which achieves quite good prediction results with a physical/statistical approach on the one hand. On the other hand, the processing time of the prediction chain could be optimised so that it lies within the specified limits

4.1.2 VERTICAL POWER FLOW FORECAST

For the investigation of the new update approach concerning the vertical power flow forecast, seven transformers were evaluated. Basis for the selection were the results from the first evaluation of the 585 vertical power flow models using the forecast system presented in D6.2 [14]. By analysing the results more deeply it turned out as expected that the used model did not perform very well for transformers whose characteristics have changed. For seven transformers, with a RMSE higher than 38% and a Pearson correlation between 0.6 and 0.8, the forecasts were especially influenced by the changing power flow characteristics of the transformer. Thus, these were found to be a good starting point for the analysis of the regular update process [9].

Regular Training Update Strategies Using LSTM Models

As already mentioned, especially the changing of the characteristics of a transformer's power flow makes it difficult to perform high quality forecasts. This is indicated in Figure 23 where the test data changes compared to data used to train the vertical power flow. The idea is to handle exact these kind of changes with a regular update respectively retraining of the model. A first model has been trained with historical data and is being retrained daily to include the most recent information, so that new behaviours of the transformers can be learned and correctly represented by the LSTM model. Therefore, two hyper-parameters, the number of epochs and the learning rate, were analysed to give higher weight to the new available data. The model architecture and additional hyper-parameters that have not been changed from the first trained LSTM model can be found in the paper [9].

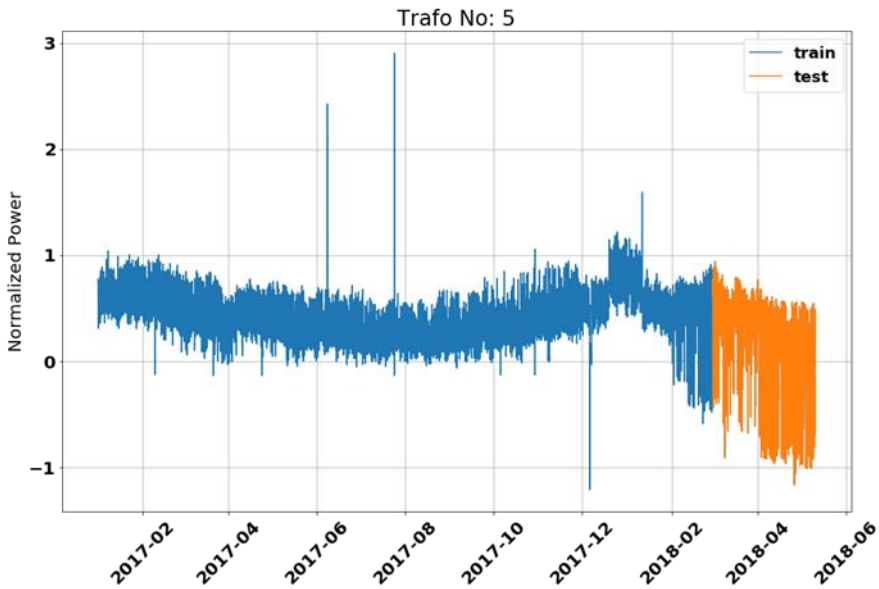

FIGURE 23 – TIME SERIES OF TRANSFORMER 5 WITH TRAINING DATA IN BLUE AND TEST DATA IN ORANGE. ESPECIALLY THE CHANGED CHARACTERISTIC OF THE TRANSFORMER IN THE TEST DATA CAN BE SEEN.

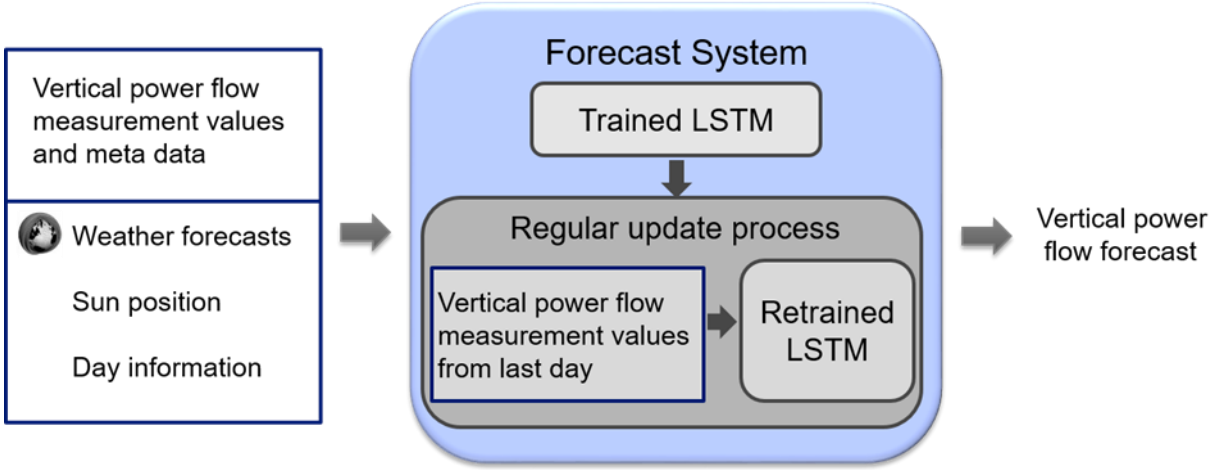

FIGURE 24 – FORECAST SYSTEM
OF THE VERTICAL POWER FLOW FORECAST (RIGHT SIDE) WITH INPUT DATA (LEFT SIDE) AND USED MACHINE LEARNING ALGORITHM (MIDDLE) IN THE WAY HOW IT IS USED IN THE PROJECT EU-SYSFLEX AND WITH ADDITION OF THE REGULAR UPDATE PROCESS (MIDDLE LOWER PART)

Baseline Models

Persistence models are usually very simple models, only using the time series itself as input for the forecasting. Although they are very simple, they are often still hard to beat, especially for low forecast horizon up to 1 hour. That is why we chose the two persistence models Persistence Last Measurement and Persistence Last Day. Furthermore, we use ARIMA as an additional baseline model.

Persistence Last Measurement

The simplest way of using a persistence model is to use only the last available measurement value and repeat it for the whole forecast horizon. At the time the forecast is calculated, this means that for the next 48 hours (maximum used forecasts horizon) the predicted values have all this same value of the last available measurement.

Persistence Last Day

Another way of using a persistence model for forecasting is to use the available measurements from the last day. This means by predicting the next hour value valid at e.g. 3pm at day 1, then the forecast gets the same value as the measurement had at the day before (day 0) at 3pm and so on. If the forecast horizon exceeds the 24 hours, it just starts over with the last day, meaning that for predicting 25 hours ahead, which would be again a value valid at 3pm for day 2, it again gets the same value from day 0 at 3pm. Summarized, creating this kind of persistence at the time the forecast is calculated, just means it predicts the exact same values from the day before for the first day (forecast horizon 0 to 24 hours) and repeats this by predicting the second day (forecast horizon 25 to 48 hours).

ARIMA

One well-known method in time series forecasting is the Auto-Regressive Integrated Moving Average (ARIMA). For ARIMA(p,d,q) models, the three parameters p (number of autoregressive terms), d (degree of differencing) and q (order of moving average model) must be configured. To determine the term d, we used the KPSS test. For the determination of p and q-values we used the auto-correlation function (ACF) and the partial auto-correlation function (PACF). We choose the largest number of time steps (for p and q) that lie outside the 95% confidence interval.

Vertical Power Flow Forecast: Setting

The analysed data set with vertical power flow measurements and weather parameter forecasts contains data from January 2016 until May 2018 and has a time resolution of 15 minutes. The data set was divided into training (all data until the 1st of January 2018), validation (1st of January 2018 until 1st of March 2018) and test data (1st of March 2018 till Mid of May 2018).

As a result of the analysing of update strategies 5 epochs and a learning rate of 0.001 were chosen as starting point for the further investigations of the regular update approach.

In order to calculate the normalized RMSE the original absolute measurements were normalized using the following equation:

$$x_{scaled} = \frac{x - Q_{0.03}(x)}{Q_{99.7}(x) - Q_{0.03}(x)}, \tag{1.1}$$

where x is the original absolute value and $x_{scaled}$is the normalized value. For the prevention of using outliers for the maximum and minimum values of x, the quantile values of the 99.7% quantile ($Q_{99.7}$) and the 0.03% quantile ($Q_{0.03}$) respectively are used instead as maximum and minimum.

Vertical Power Flow Forecast: Results

In Figure 25, forecasts without and with a regular retraining for the transformer with the number 5 are compared. Since the forecasts calculated in the regular update process need to start with the validation data, it is also plotted in the lower plot (Figure 25a). The blue time series mark the training/validation data and the black time series mark the test data from the vertical power flow true measurements. In both plots the forecasts are plotted for three forecast horizon: the 1 hour, 4 hour and 48 hour. In the upper plot Figure 25a (left side) and Figure 25b (right side) is the forecast without any update of the LSTM model shown. We see that (on the test data) the predicted values are too low for each forecast horizon. In contrast, the forecast using the regular update process reaches the entire range of newly scaled test data which can be seen in the lower plot Figure 25a and Figure 25b.

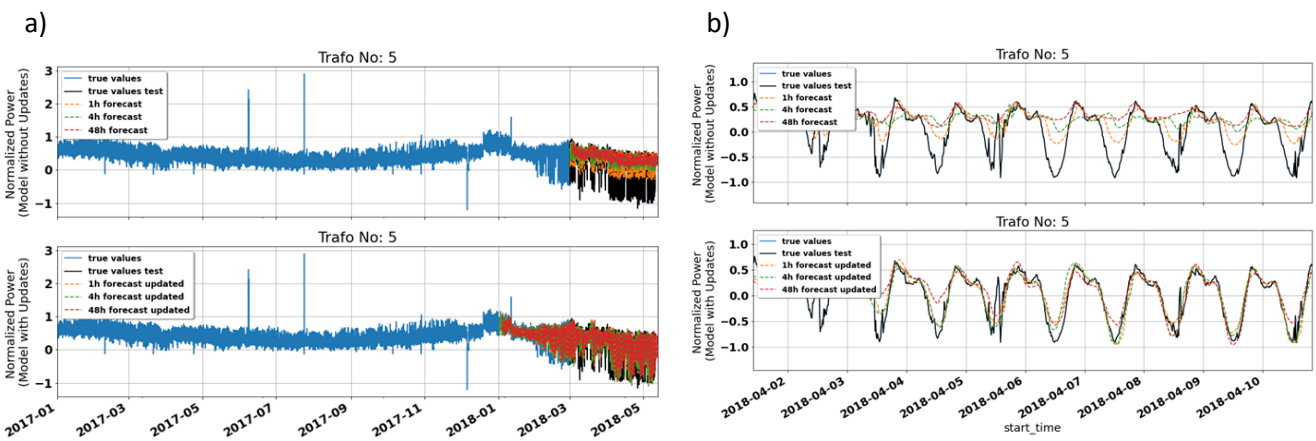

FIGURE 25 – TIME SERIES PLOTS WITH FORECASTS OF THE 1, 4 AND 48 HOUR HORIZON AND TRUE MEASUREMENT VALUES. THE BLUE LINE MARKS THE TRAINING AND VALIDATION DATA AND THE BLACK LINE THE TEST DATA. THE UPPER PLOT CONTAINS THE LSTM MODEL RESULT

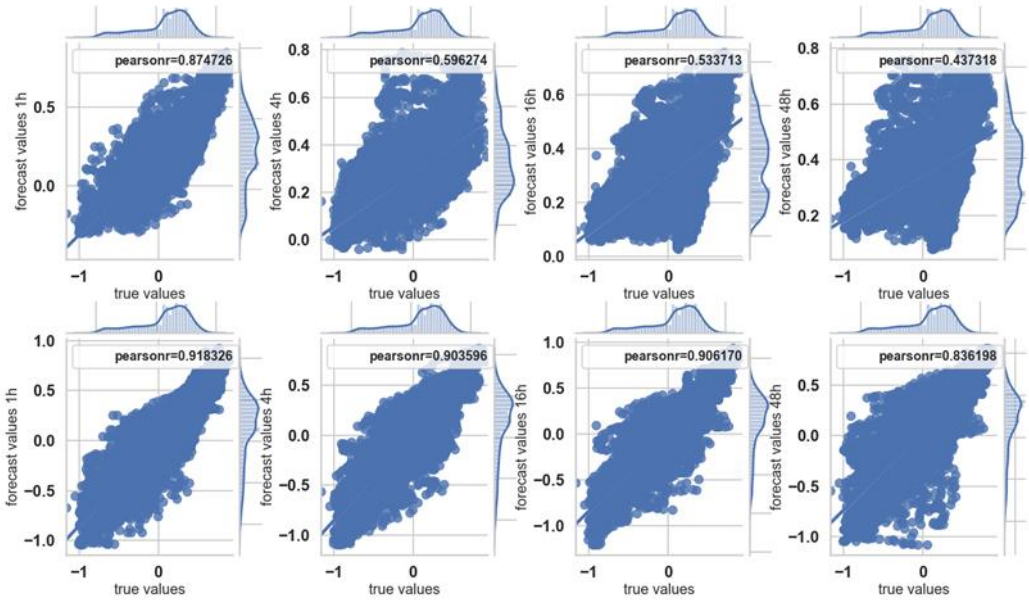

FIGURE 26 – SCATTER PLOTS FOR 4 DIFFERENT FORECAST HORIZONS (1H, 4H, 16H, 48H) FOR TRANSFORMER 5. THE TRUE MEASUREMENT VALUES ARE PLOTTED AGAINST THE FORECAST VALUES. IN THE UPPER PLOT, THE FORECAST RESULTS FROM THE LSTM MODEL WITHOUT USING THE REGULAR RETRAINING.

In order to get a more complete, somewhat deeper insight, also with regard to the forecast horizons, we have zoomed into the figure once again. This can be seen in Figure 25b. The correlation of the forecasts, meaning with all shown forecast horizon, with a regular update process are much higher than without it.

This conclusion is also presented in Figure 26 where a scatter plot for four forecast horizon and again without and with a regular retraining is used. To the previous used forecast horizon in Figure 25a and Figure 25b, the 16 hour horizon is added. The scatter show the relation between the forecasts (y-axis) and the true measurement values (x-axis). A line for comparison shows the case if the model had learned the exact relationship between the explanatory variables and the vertical power flow measurements. In the upper plot, there is a moderately strong linear relationship between the forecasts and the measurement values without updating the model. The correlation gets worse the higher the forecast horizon gets (from left to right). In contrast to the figure below, where the regular update process is used. Here, a stronger linear relationship between forecasts and measurements with a higher correlation for each forecast horizon can be seen.

Comparison: LSTM, LSTM with Updates and Baseline Models

In order to evaluate the performance of the used LSTM model architecture with and without using the regular update process, we compared the forecast results with the three baseline models: persistence using last 24 hours (persistence_24h), persistence of the last value (persistence_last) and ARIMA (model_arima) . For ARIMA the parameters p, d and q must be specified. Using the procedure described in Section 'Baseline Models' we determined the three values for each transformers separately. The forecast results are shown in Figure 27. The results are again presented aggregated over all seven transformers and for the seven forecast horizons: 1h, 4h, 8h, 16h, 24h, 32h and 48h. As error measure, the normalized RMSE is used. It is clear to see that the LSTM model architecture using the regular update of the model outperforms all other models, with the exception of the ARIMA model, which

clearly performs best for the forecast horizon of 1h. One fact that explains the poorer performance of the LSTM model (with regular updates) compared to the ARIMA model for the 1h forecast is that the LSTM is not explicitly optimised for the 1h forecast horizon. However, for all other forecast horizons, the ARIMA model is the weakest performer. Regarding the LSTM model without update process, it only exceeds in the 1h forecast horizon the persistence model using the last day, described in Section 'Baseline Models'. For the other forecast horizons, it outperforms only the ARIMA model and the persistence model using the last available measurement value, for the forecast horizons of 4h, 8h, 16h and 32h.

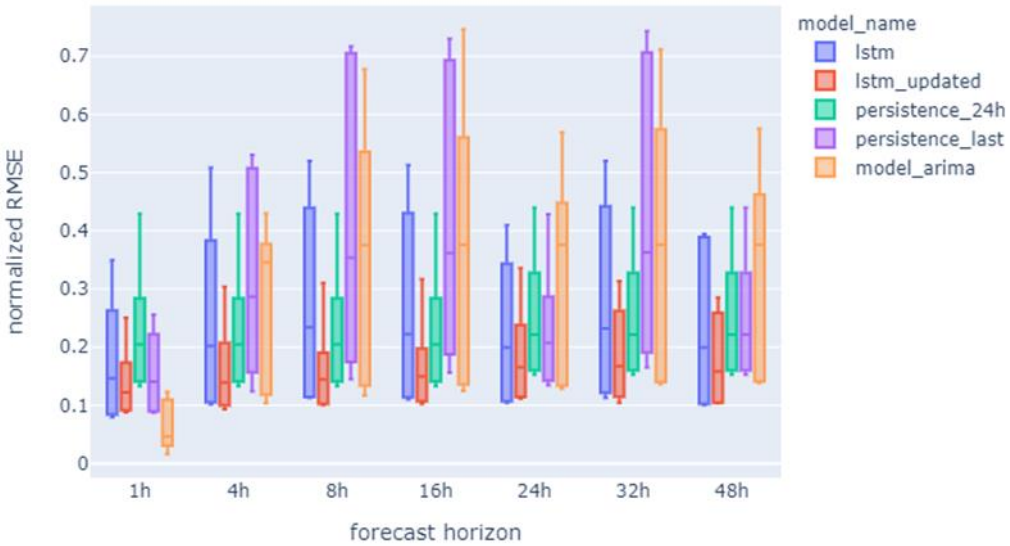

FIGURE 27 – BOXPLOT OF NORMALIZED RMSE WITH A COMPARISON OF DIFFERENT MODELS
FIRST TRAINED LSTM WITHOUT UPDATES (LSTM), LSTM WITH UPDATES (LSTM_UPDATED), PERSISTENCE USING LAST 24 HOURS (PERSISTENCE_24H), PERSISTENCE OF THE LAST VALUE (PERSISTENCE_LAST) AND ARIMA

Apparently, the forecast horizon of 24h and 48h are easier to predict, especially for both persistence models. The reason could be that the vertical power flow has a similar repeating pattern on a daily basis, which is usually the case if the consumption is predominating over the volatile generation. This is actually for most of the seven transformers the case.

Finally, we evaluated for all seven transformer and all seven forecast horizon the improvement of the normalized RMSE gained by using the regular training update (see Figure 28). An improvement can be achieved for all transformers, although for three transformers this is only true for some forecast horizons. These transformers provide a maximum improvement of about 1.4%. On the other hand, the other four transformers show a mean improvement of more than 7.5% for all forecast horizons. However, in average a performance reduction of 1.2% must be accepted for the other three transformers.

FIGURE 28 – IMPROVEMENT OF THE NORMALIZED RMSE
GAINED BY USING THE REGULAR TRAINING UPDATE COMPARED TO THE LSTM MODEL WITH REGULAR UPDATES.

DISCUSSION AND OUTLOOK

In this chapter, we presented a novel approach using a regular update process in combination with a previous trained LSTM model and compare both performances. In addition, we compare our model with an ARIMA model and two persistence baseline models. In a first evaluation, the optimal strategy for the update process was determined. For this purpose, the best number of epochs and the best learning rate were identified. In a second evaluation, the LSTM model using the resulted best update strategy is used for the comparison to the other models. Overall, the results show that high performance is achieved by our new approach. In average, it performs significantly better for all transformers than the other considered models. In our experiments, a significant improvement of 8% (in average) could be observed using the LSTM model with regular update process. For future work, to further improve our models, we want to consider transfer-learning approaches. This offers the possibility to cover further challenges, especially those posed by the changing characteristic of the transformers. Additionally to the presented work, we compared the LSTM model to an Encoder Decoder architecture using ConvLSTM2D [13] layers and Attention layers. Unexpectedly, we did not achieve a better result, so that we did not include the results into this paper. There should be further work to investigate the Encoder Decoder architecture more deeply. Finally, we suggest comparing our results to the method described in [12].

4.2 STATE ESTIMATION

In this section, the state estimation in the German demonstration is evaluated. The accuracy of the state estimation is key. Due to the architecture of the demonstration that follows the requirements of the grid control architecture of MITNETZ STROM, the analysis (Figure 29) is divided in the four grid regions of MITNETZ STROM.

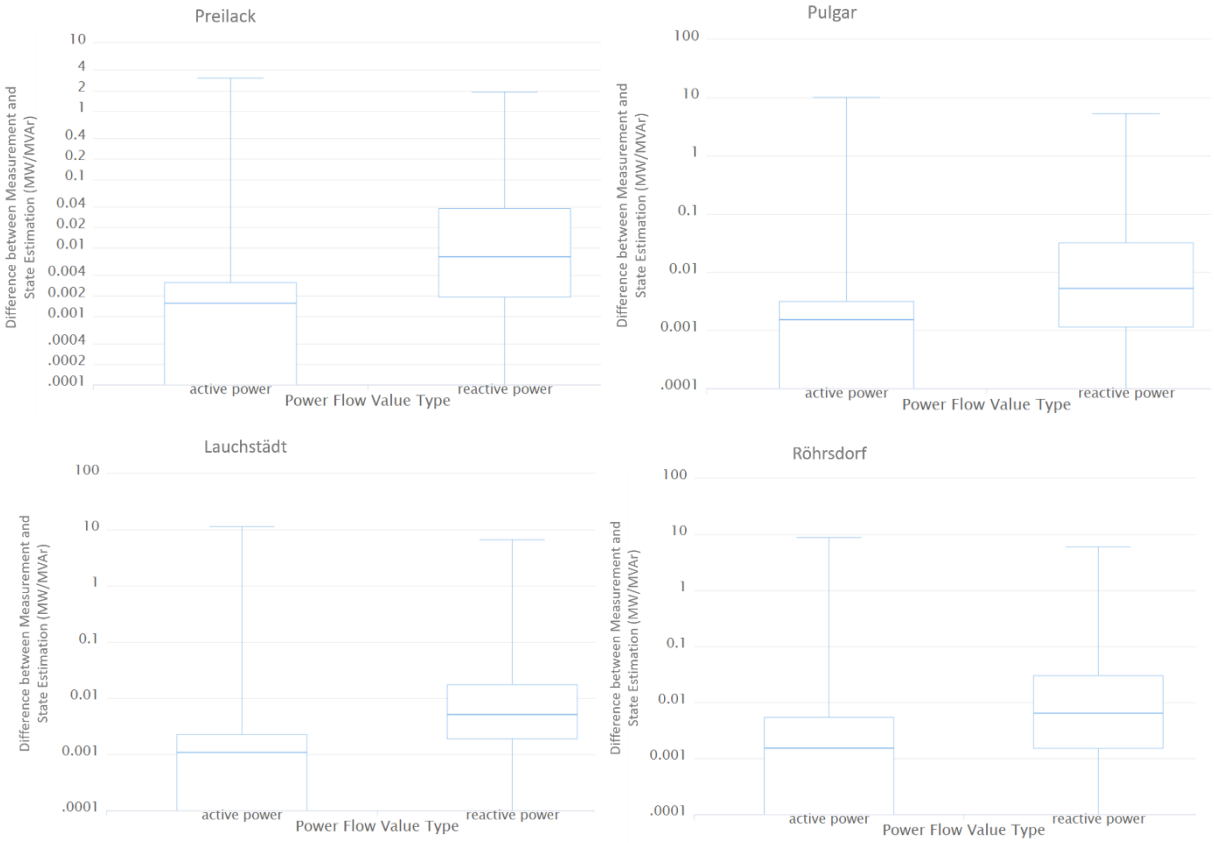

FIGURE 29 – ACTIVE AND REACTIVE POWER DEVIATIONS OF MEASURED AND ESTIMATED VALUES IN THE FOUR GRID REGIONS OF MITNETZ STROM

The Figure 29 shows the accuracy of estimated active and reactive power values. As it can be seen, the accuracy of active power estimation is higher than of reactive power estimation. Due to the higher non-linearity, it was expected. Overall, the achieved accuracy is at the same level as the measurement error. Therefore, the developed state estimation tool meets the requirements to be used.

4.3 REACTIVE POWER FLEXIBILITY EXPLOITATION AT TSO-DSO INTERFACE UNDER UNCERTAINTIES

Reactive power is crucial for a seamless operation of electrical grids. Especially grids with a high penetration of weather dependent volatile distributed energy resources (DER) have a high demand on reactive power in times of high energy injections from these DER. Fortunately, the DER can, in general, supply the needed reactive power on their own. However, also due to the high penetration of DERs in electrical power systems, it is also essential for grid operators to co-ordinately solve grid congestions (line loading and voltage violations) with available active (P) and reactive (Q) power flexibilities of integrated DERs. This requires a very accurate knowledge about the available active and reactive power and about the dependency of Q from P for each DER. Since short-term operational planning strongly depends on forecast data of generation and consumption which consists of prediction errors, intrinsic uncertainties are introduced in the simulation and have to be taken into account.

In this investigation, the dependency of Q from P for certain DER is focused as well as the amount of uncertainties, which has to be considered.

4.3.1 UNCERTAINTY OF Q(P)

In general, there are two kinds of DER:

Type 1: HV/MV non-controllable Q

Type 2: HV/MV controllable Q

Type 1 is not directly controllable by ICT means and consists of a local Q-controller. This controller is parameterized and not always well known to the DSO. However, its behaviour can be deduced from time series data.

Type 2 is directly controllable by ICT means and can be assumed to provide an accurate desired amount of reactive power for a given set point.

In this investigation, we will focus on Type 1 DER. In Figure 30, two general cases of Type 1 DER are plotted. On the left side of Figure 30, a highly correlated behaviour is shown and on the right side, an uncorrelated behaviour is shown. For Type 1 correlation, we can describe the controller by a linear approximation and the width of the distribution describes the uncertainty. For Type 2 correlation, one can assume, more or less, an equal distribution of reactive power over the range of active power, which also consists of a very high uncertainty.

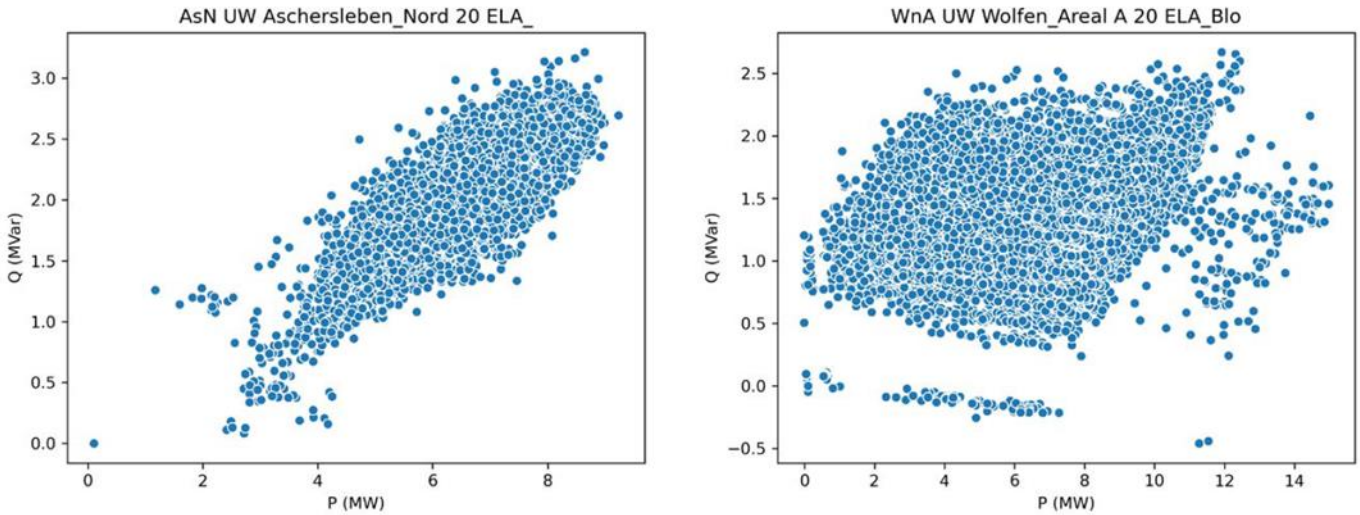

FIGURE 30 – CORRELATION BETWEEN P AND Q FOR TWO DIFFERENT TYPES OF CONTROLLED DER.

4.3.2 IMPACT STUDY OF UNCERTAINTIES ON GRID CALCULATION OND OPTIMISATION

In this part, we study the impact of uncertainty on grid calculations and optimisations. As we saw and mentioned on the previous part, we have different kind of uncertainties, which enter our computation:

1. Measurement Errors
2. Forecasting Errors
3. Respond and Controller Errors

For the study, we generalize the uncertainties and assume that we have only one uncertainty, which consist of the three mentioned types. We assume the aggregated error to be either about 5% (small error case) or about 20% (large error case).

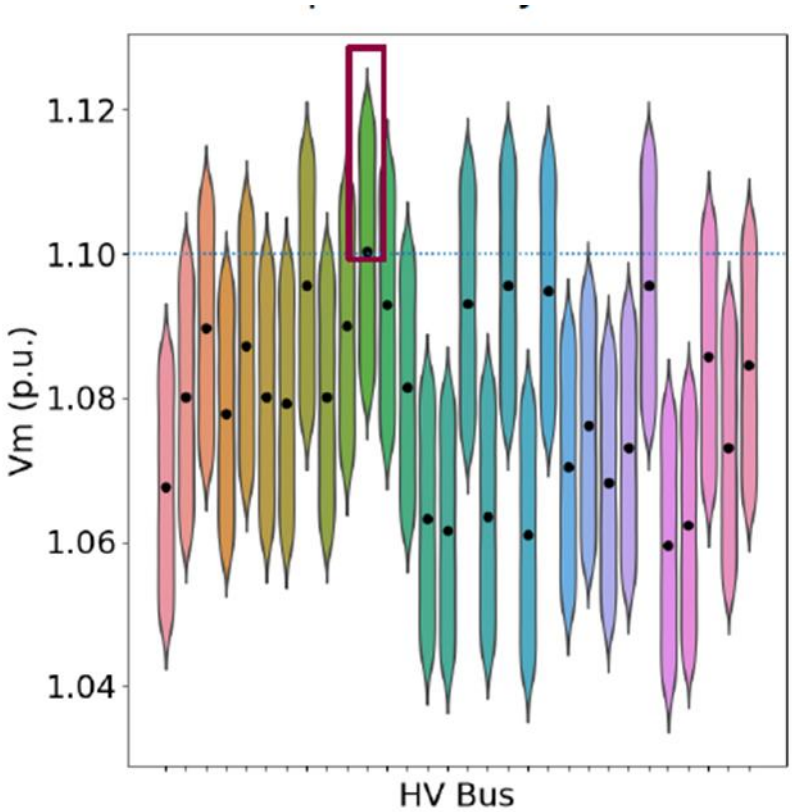

FIGURE 31 – BUS VOLTAGES WITH UNCERTAINTY RANGE BASED ON PROBABILISTIC LOAD FLOW STUDIES.

In order to investigate the impact of uncertainties on different elements in the grid, we use probabilistic power flows. I.e. we run a large number of power flows and vary the input parameters of Q for DER according to the uncertainty range. In Figure 31, we plotted the bus voltage distribution for several buses. One can see, that for most buses, even when the average voltage magnitude is way below 1.1 p.u. (which is the voltage limit), due to uncertainties in reactive power generation, forecasts and measurements, cases exist that could violate grid voltage restrictions. In addition, when using optimisation methods to control the reactive power at grid connection points (GCP), one has to expect the actual value, which results at GCP to be different from a desired set point. In Figure 32, the EU-SysFlex optimisation approach was used to coordinate reactive power at GCPs. Using our probabilistic approach, we can see that even for a relatively small uncertainty of 5 % the resulting reactive power flow has a range of about 10 MVar. For the 20 % uncertainty scenario, we even get a range of about 20 MVar. That also means, if the maximal Q-potential is given as set point, it can be that this value might not be reached.

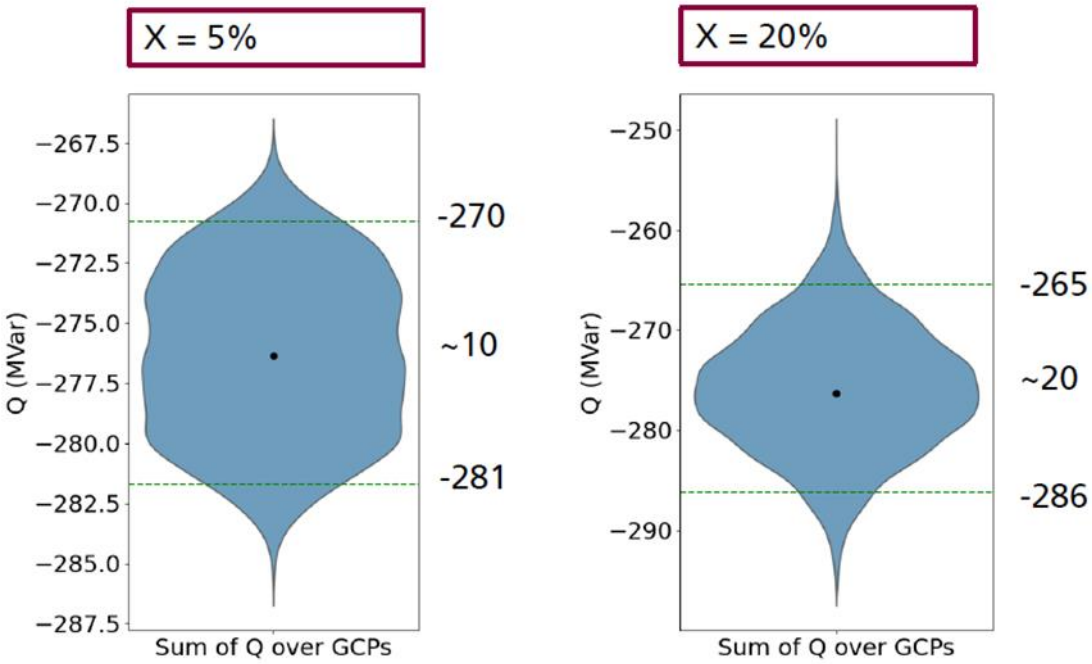

FIGURE 32 – REACTIVE POWER DISTRIBUTION FOR A GIVEN Q-SET POINT FOR TWO DIFFERENT UNCERTAINTY SCENARIOS SET-POINT OF -276MVAR AS A SUM OVER ALL GCPS, UNCERTAINTY SCENARIOS: 5% (LEFT) AND 20% (RIGHT)

4.3.3 TIME SERIES SIMULATION

In a time series simulation, it was investigated how large uncertainties in reactive power potentials at GCP (in this case minimum Q potential) are and which values can certainly be reached. In Figure 33, simulations were performed which includes different sources of uncertainties (stemming from measurements of DSO, TSO or both). One can see two connected sets of simulations, which resemble either the 95%-quantile or the 5%-quantile. That means that in the 95%-case, most of the results can reach at least the shown value in the range of its uncertainty. The 5%-case shows the 5% cases, which reach the minimum amount of reactive power at GCP in the range of its uncertainties. One can also see, that the spread (or gap) between both quantiles is not constant over the course of the day and can be larger or smaller.

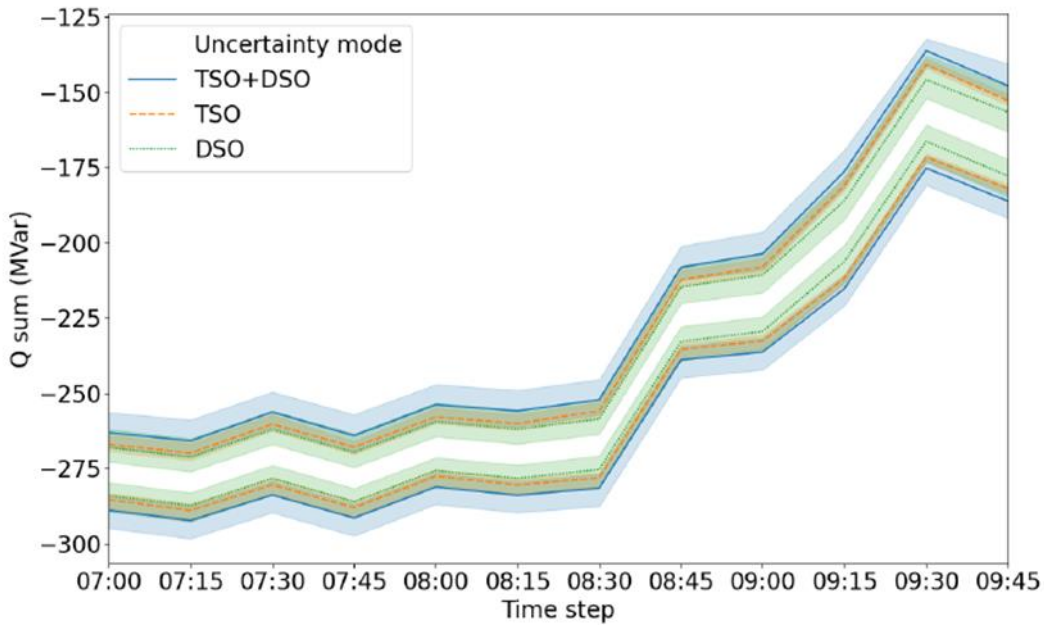

FIGURE 33 – UNCERTAINTY BAND AROUND THE MINIMAL REACTIVE POWER SET POINT POSSIBLE. THE COLORED LINES AND SHADED AREAS CORRESPOND TO UNCERTAINTY EFFECTS REASULTING FROM DSO, TSO OR BOTH. THE UPPER LINES AND AREAS CORRESPOND TO A 95% QUANTILE AND THE LOWER ONE TO A 5% QUANTILE. THE LATTER MEANING THAT ONLY 5% OF THE RESULTS REACH VALUES IN THIS RANGE AND THE FORMER ONE THAT 95% OF THE RESULTS REACH AT LEAST THIS AMOUNT OF Q.

From the above analysis, one can conclude that uncertainties from various sources strongly affect the resulting reactive power output of DER. Hence, one has to include secure margins in order to avoid voltage constraint violations and take these uncertainties for reactive power potentials at GCP into account.

4.4 SCHEDULE-BASED CONGESTION MANAGEMENT

After explanation of deviation sources in the functionality chain of the German demonstration, like forecast, estimation and measurement uncertainties in the previous subchapters, the main objective is analysed. This objective is the development of schedule-based congestion management. The evaluation of the congestion management is highly complex, especially when introducing schedule-based congestion management. Therefore, the benchmark is today's real-time curtailment regime. The comparison of schedule-based and real-time congestion management is shown in Figure 34. The curve of "measured infeed – curtailed" in Figure 34 represents the results of today's curtailment regime for the same generators that are considered as active power flexibility in the German demonstration. The curve "forecasted infeed – congested grid" represents the forecasted infeed of the same set of generators without considering whether there is a congestion or not. As can be seen in the difference between this curve and the curve "adjusted infeed – congestion free" the demonstration's tool predicts a congestion. The curve "adjusted infeed – congestion free" represents the proposed set points of generators in the 110 kV grid as result of the German demonstration.

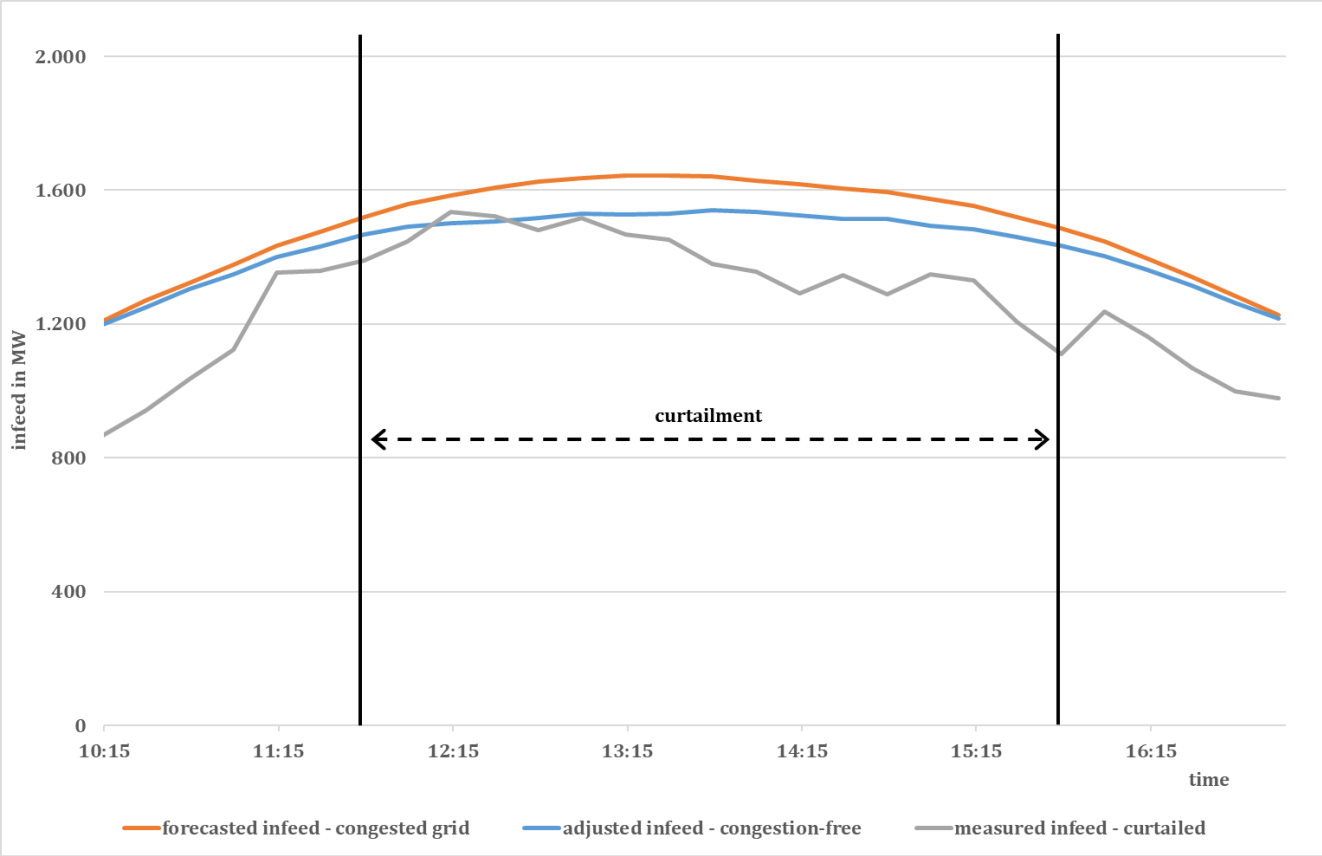

FIGURE 34 – COMPARISON OF GRID STATE

In Figure 34, the infeed in a part of the grid of MITNETZ STROM is shown. The period marked with curtailment indicates the time when today's curtailment regime was needed to prevent an overload in n-1 case. It needs to be pointed out that both today's curtailment regime and the introduced schedule-based congestion management belong to preventive congestion management, meaning that actions are taken to prevent overloading that would occur in case of fault of an asset before the fault happens. The innovative tool of the German demonstration is designed to reduce the flexibility needed for active and reactive power management. Today's curtailment regime can consider active power management only. In addition, due to technical restrictions, based on historical economic development, the precision of activation is limited. Due to the focus on HV grid in the German demonstration, congestions occurring in MV or in the HV/MV substation are not considered.

The calculation is based on forecast from 9a.m. and as can be seen in Figure 34, a deviation before the curtailment period appears. This deviation is caused by different reasons. The main cause is that the developed process starts with receiving schedules from aggregators for each power plant to consider reduced infeed due to maintenance and untraded energy on wholesale market. The integration of aggregators in the German demonstration was not possible and so prediction is based on forecast. At the beginning of the curtailment period, regardless of the deviation, a grid without congestions is secured. The deviation that starts in the middle of the curtailment period is on the one hand based on uncertainty due to forecast horizon and on the other hand based on curtailment in lower grid level that the German demonstration is neglecting. Therefore, under these circumstances the evaluability is complex. The maximum of needed capacity to activate as flexibility is reduced by the German demonstration, see Figure 35.

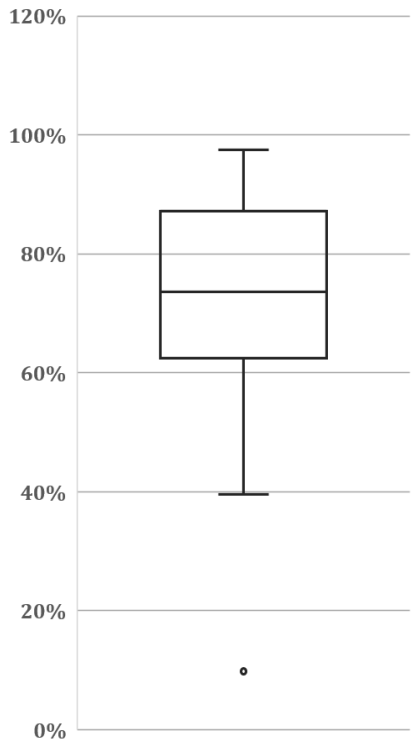

FIGURE 35 – AMOUNT OF MAXIMUM CAPACITY OF NEEDED FLEXIBILITY

As Figure 35 shows, the German demonstration approach reduces curtailment in all investigated cases. The benchmark of 100% represents the old curtailment regime. The reduction varies from 0 % (close to the benchmark) to 90 % (open dot as extreme value in the box-plot). Thus, the power curtailed from DER units is lower with the demonstration's approach, but only for maximum capacity. As can be seen in the example of Figure 34, in some cases the period of flexibility need could be longer. Since settlement is out of scope of the German demonstration, the analysis of curtailed energy is not feasible. This indicates further need of investigation. It was not foreseen in project planning, but a case study to evaluate the accuracy of the approach can be found in Deliverable D6.3 [15].

4.5 GRID LOSSES

Another aspect of the German demonstration is the reduction of grid losses. Since optimisation algorithm needs a target and in case external flexibility request is missing, the overall target of the optimisation of the German demonstration therefore is to reduce the grid losses. As shown in Figure 36, yearly grid losses can be reduced with the developed IEE.NetOpt tool. Today's static settings cause energy losses in the grid of approximately 155 GWh. With introducing the IEE.NetOpt tool into grid operation, not only flexibility potential could be provided for TSO, but also these grid losses could be reduced.

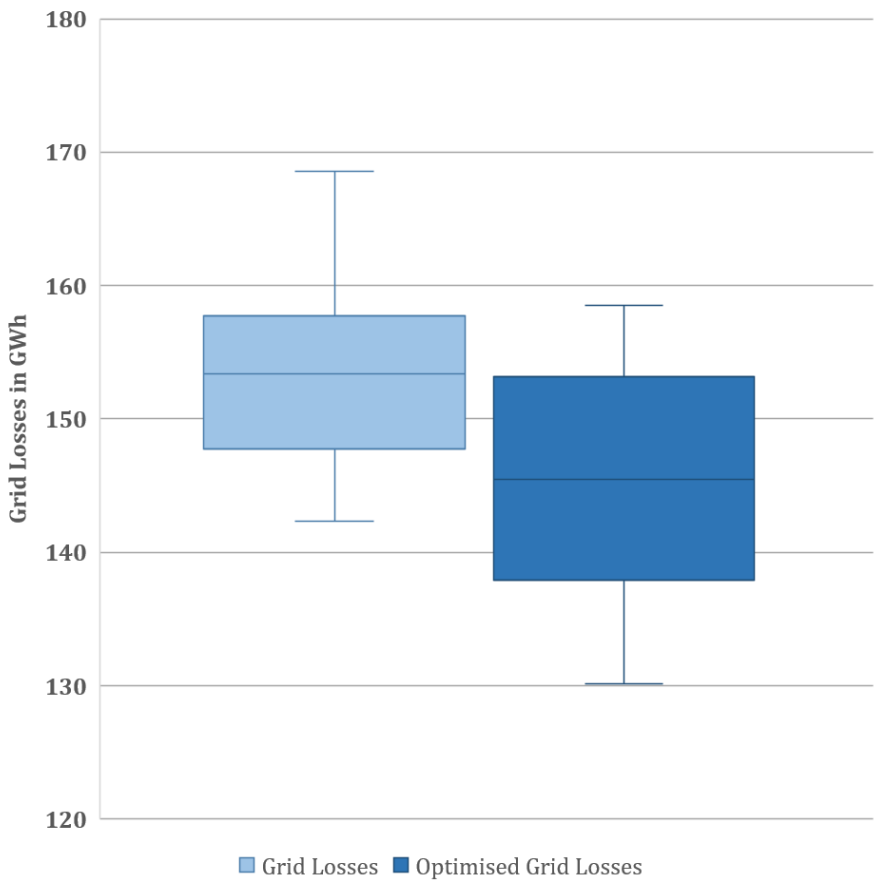

FIGURE 36 - YEARLY GRID LOSSES IN HV GRID

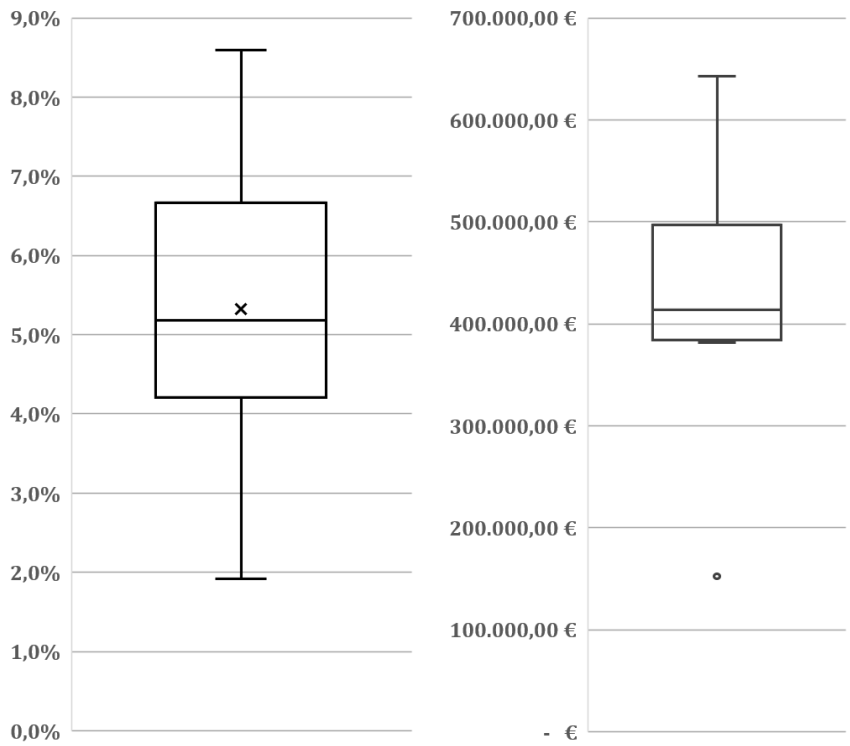

FIGURE 37 – REDUCTION OF LOSSES AND RESULTING SAVINGS

The potential of reduction depends on available flexibility. Because the flexibility is provided by RES, the reduction potential is limited in times with bad weather conditions and therefore low infeed. The spread of savings in Figure 37 is caused by such uncertainty. The savings are based on an electricity price of 50.79 €/MWh and approximately 5 % of grid losses could be reduced in the distribution grid of MITNETZ STROM.

4.6 PROCESSING TIME

This chapter presents a statistical evaluation of the time required to perform the optimisation of the following four parts of the network:

- Pulgar;
- Lauchstädt;
- Röhrsdorf;
- Preilack.

The processing times considered are the combination of the optimisation run time and of the data acquisition for the optimiser. The data processing time combined for all processes in current network should not exceed the frequency of fact time series coming, namely 15 minutes. The data processing time combined for all processes in forecast network should not exceed the frequency of forecast data coming, namely 30 minutes.

The acquisition time is limited and does not exceed three minutes in normal data transmission mode. Data transmission mode is implied normal in case all data communication and transmission channels work properly.

The optimisation run time for each object is different and depends directly on the runtime of the optimiser itself e.g. its calculation modules, as well as on the speed of data transmission to the optimiser for a particular object. In other words, the optimisation time represents the running time of the entire optimisation from start to obtained calculation results, basically, the time difference between the beginning and the end of the optimisation. The target for the optimisation process is to reduce the time difference to less than 5 minutes (300 seconds). In this approach, the time difference is considered as the main optimisation score indicating optimiser performance. Thus, the emphasis in this section is placed on the analysis of an optimisation score. Optimisation is assumed normal if optimisation score does not go beyond the five-minute limitation. In case the optimisation for a certain part of the network took longer than the five-minute threshold, the optimisation is considered critical and requires further in-depth examination to find out the underlying factors.

The calculation of optimisation score for each part of the network is performed once a day and based on time series coming over the day with a frequency of once every 15 minutes. Hence, the outcome of the optimisation score calculation is a regular 15-minute time series with time difference value (duration of optimisation in seconds) calculated for each time interval.

Of greatest interest are the observations for the current network, as they provide a description of the ongoing real picture and give an estimate of the implemented calculations.

4.6.1 OPTIMISATION EVALUATION FOR CURRENT GRID

The first approach underlying the statistical analysis is to compare the calculated values of the time difference by days of week. For each part of the network, two graphs are presented – a combined time series charts graph with line plots and a histogram with kernel density estimation (KDE).

On each time series chart, represented by multiple line plots, the line for the marked day is brightly coloured; the lines for the other days of a week are coloured in grey - just for a visual comparison. The red dotted horizontal line represents the threshold value of 5 minutes, i.e. 300 seconds. The solid curve marked in red above the other curves is a moving average for a particular day.

On each histogram, the height of the each bar is characterized by a number of time difference values falling on the corresponding range of the time difference. The moving red curve over the each histogram is KDE, representing a probability density estimator.

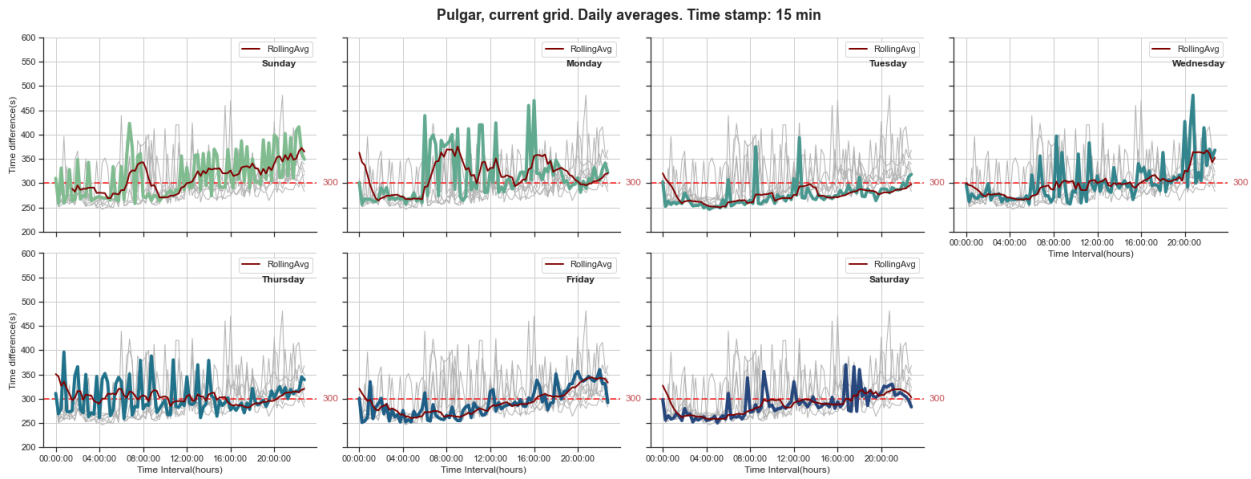

FIGURE 38 – TIME SERIES LINE PLOTS. DAILY MOVING AVERAGES. OBJECT: PULGAR (CURRENT GRID)

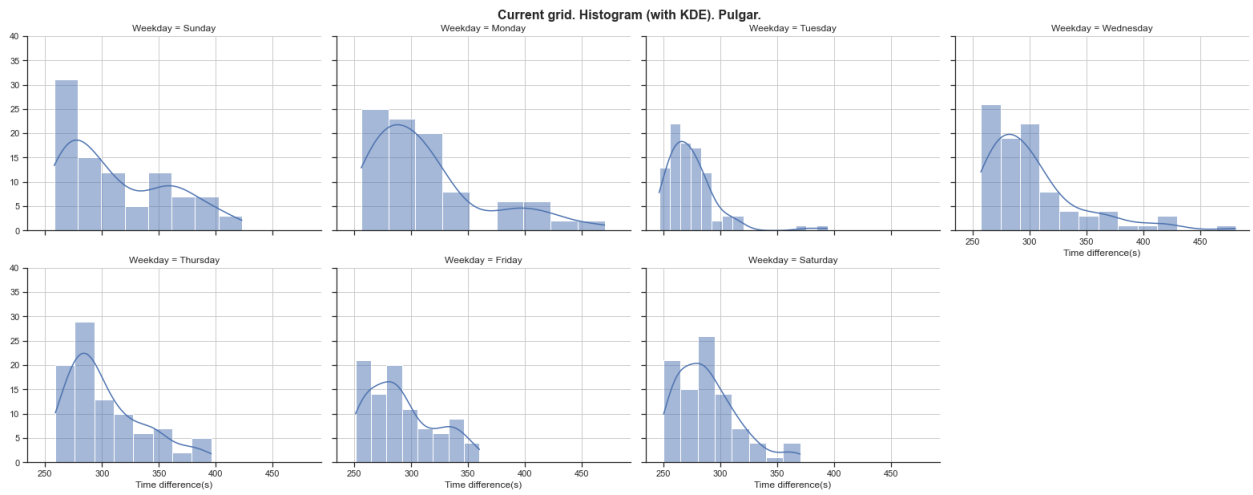

FIGURE 39 – HISTOGRAM WITH KDE. OBJECT: PULGAR (CURRENT GRID)

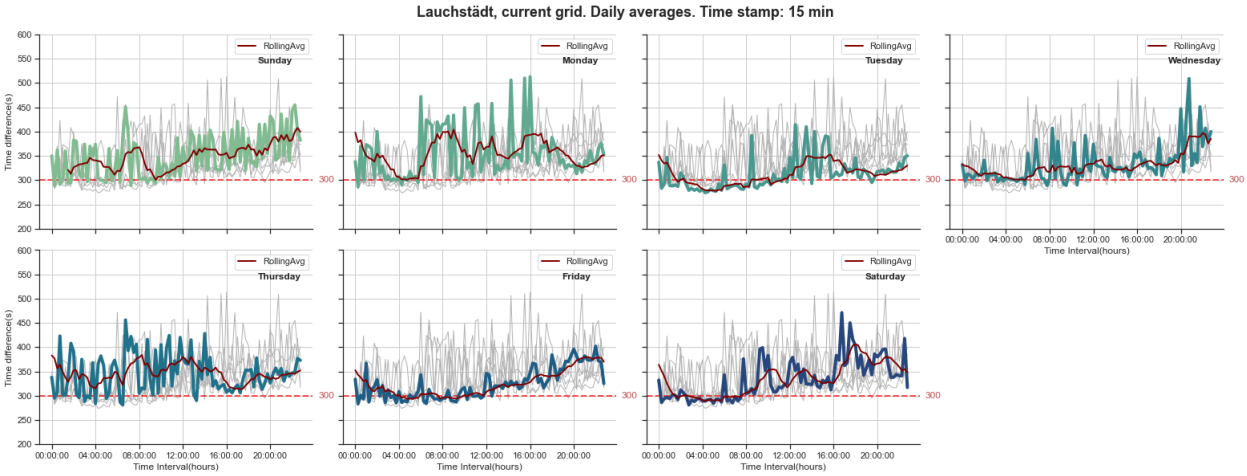

FIGURE 40 – TIME SERIES LINE PLOTS. DAILY AVERAGES. OBJECT: LAUCHSTÄDT (CURRENT GRID)

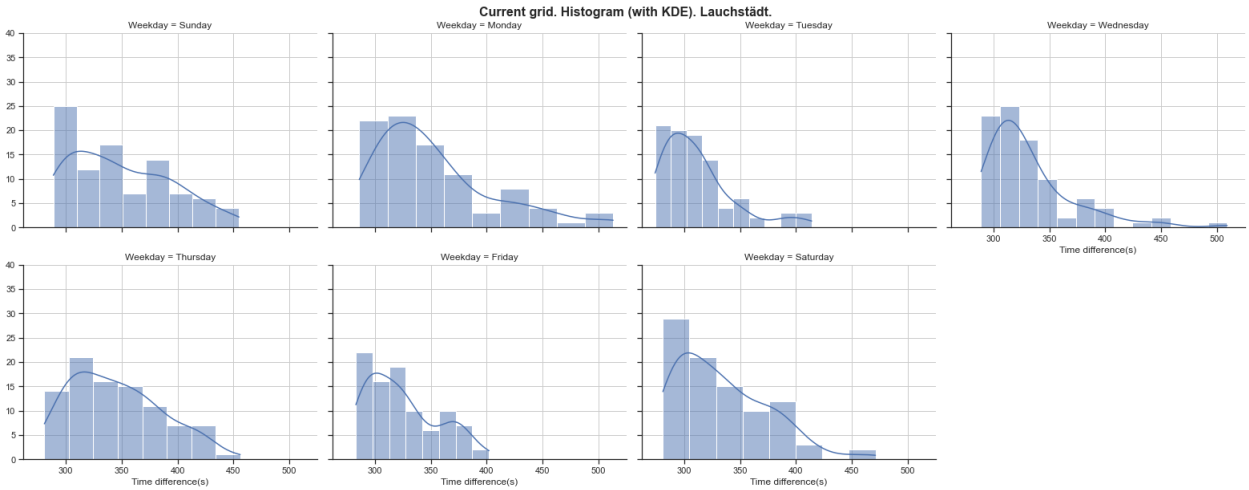

FIGURE 41 – HISTOGRAM WITH KDE. OBJECT: LAUCHSTÄDT (CURRENT GRID)

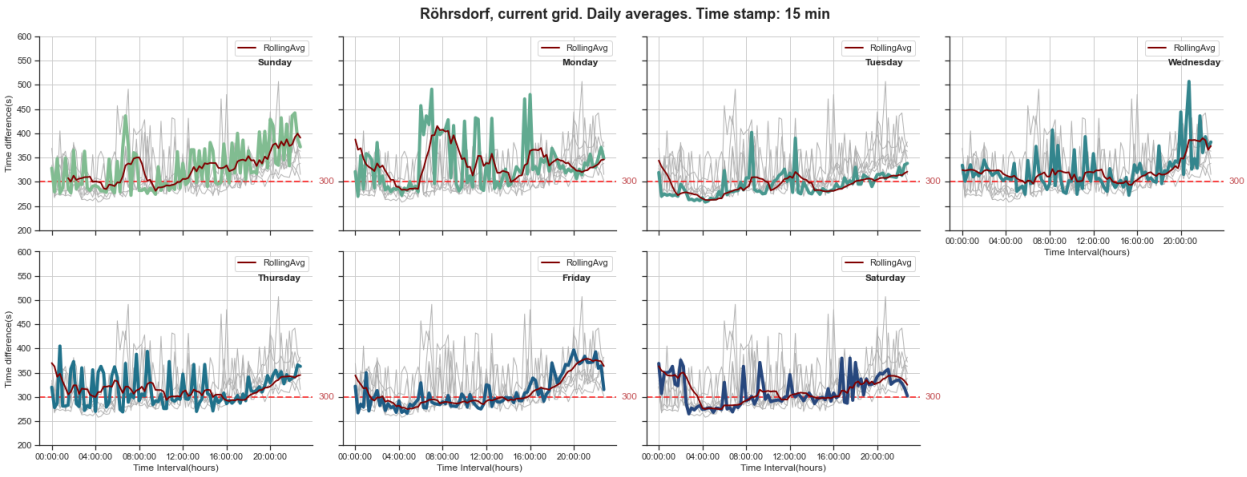

FIGURE 42 – TIME SERIES LINE PLOTS. DAILY AVERAGES. OBJECT: RÖHRSDORF (CURRENT GRID)

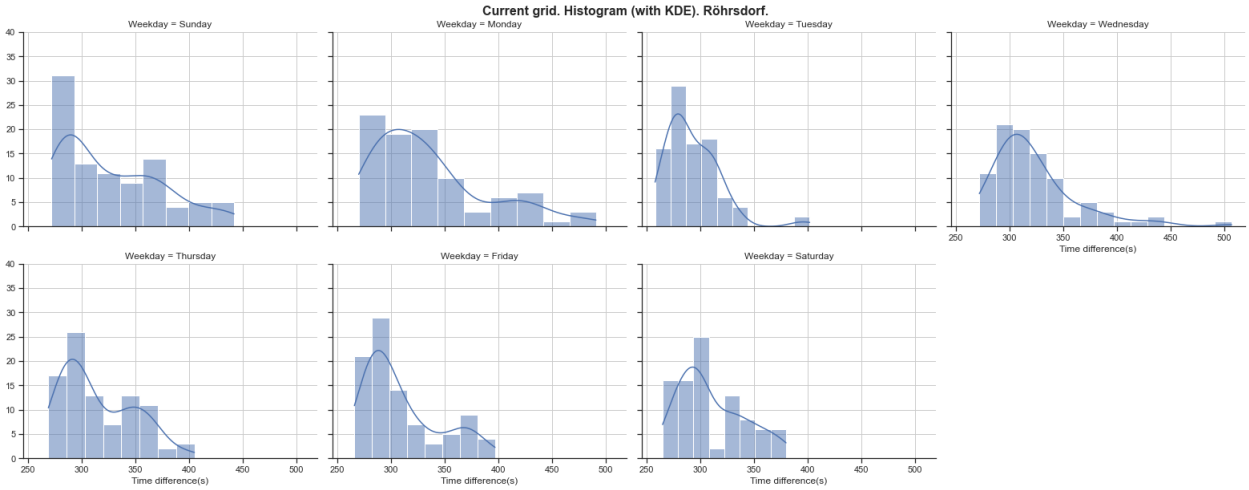

FIGURE 43 – HISTOGRAM WITH KDE. OBJECT: RÖHRSDORF (CURRENT GRID)

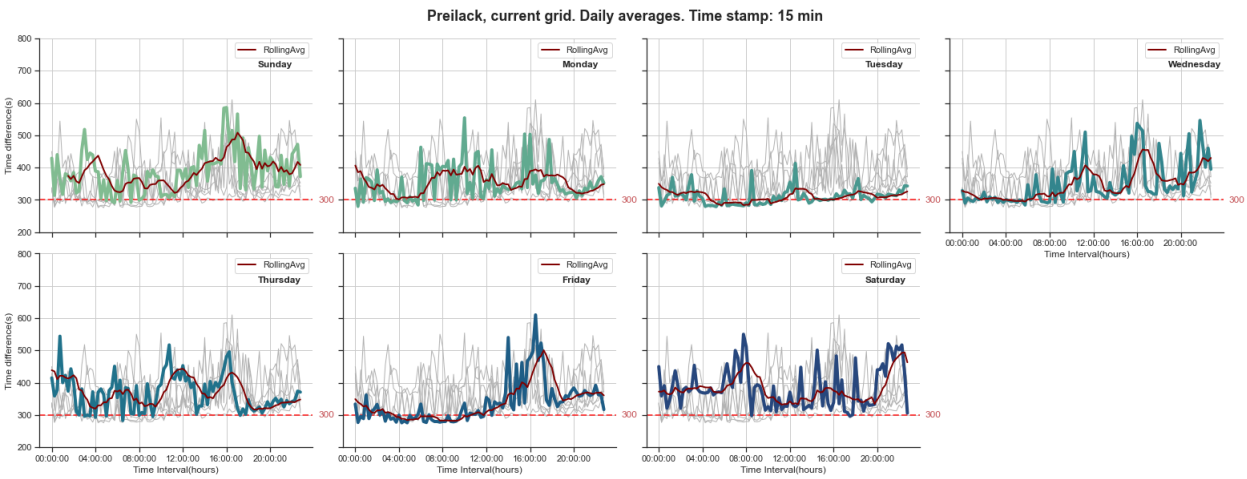

FIGURE 44 – TIME SERIES LINE PLOTS. DAILY AVERAGES. OBJECT: PREILACK (CURRENT GRID)

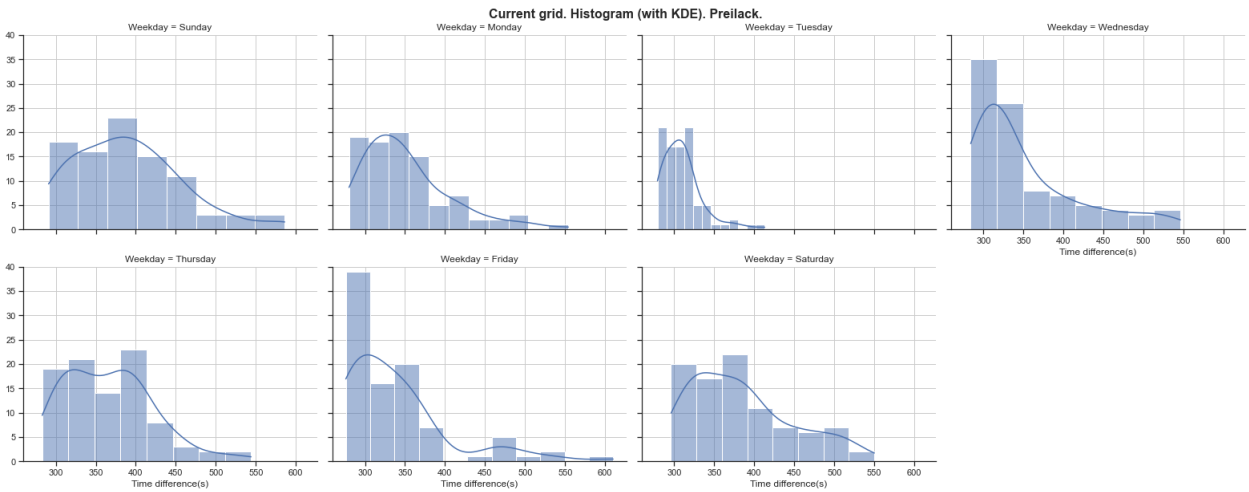

FIGURE 45 – HISTOGRAM WITH KDE. OBJECT: PREILACK (CURRENT GRID)

Figure 38, Figure 40, Figure 42Figure 44 show combined time series line plots reflecting the daily dynamics of optimisation score at 15-minute calculation intervals. Each brightly coloured (green-blue) time series line plot for a

particular weekday is constructed by averaging the values for the corresponding time intervals over all the time series associated with that weekday. According to the obtained charts, the following conclusion is made: the optimisation time has significant variations not only between days but also intraday, which means that calculations for each time interval are performed unevenly. This can be driven both by speed of data transmission to optimiser and speed of data processing and calculation by optimiser modules. The optimiser's data processing speed also depends on the complexity of particular network. According to the graphs shown, the most stable part of the network for the optimisation is Pulgar. Its time difference values are mostly below the five-minute optimisation threshold (red dashed horizontal line on the graph). Preilack is considered the least stable for optimisation. Besides, the time difference values calculated for Preilack are mostly above the five-minute optimisation threshold, indicating a critical optimisation level for this facility and requiring more thoroughly investigation despite the fact, that even at a critical optimisation level this part of the network generally fits a 15-minute processing time interval A moving average based on rolling 7 days (curve «RollingAvg» marked in red) is used to analyse optimisation score by calculating of rolling averages for each seven values of the complete data set taken for a particular day. This curve mostly focuses on determining the long-term trend of optimisation by smoothing out short-term fluctuations. The largest number of fluctuations occurs at the end of the week and also in the first half of the day on Mondays and Wednesdays. This is high-probably caused by interruptions in data transmission channels e.g. data transmission delay due to the overload of the enterprise networks.
Below each time series line plots graph presented is a histogram with kernel density plot (KDE), created similarly for particular object for each weekday (see Figure 39,Figure 41,Figure 43 and Figure 45). These graphs are based on the same averaged data that underlie the combined time series line plots. However, their main purpose is to draw insights from the data through their distribution. This helps to determine a central trend of the data, a range of their observations and a frequency of data belonging to a certain interval. It is one of the most common statistical approaches to data visualizing. A histogram is a bar chart where the axis characterizing the data variable is divided into a set of discrete segments, and the number of observations falling into each segment is displayed with the height of the corresponding bar. The presented histograms are heavily skewed in left direction. This indicates that most of the values of the optimisation score (time difference) fall in the interval up to 300 seconds and thus proof a normal optimisation behaviour.

A nonparametric way to estimate the data distribution is the kernel density estimates (KDEs) in comparison. The KDE plotting is based on a Gaussian kernel, which is used to smooth out the values. For each object, a KDE curve is plotted (Figure 46) and combined on one graph for comparison.

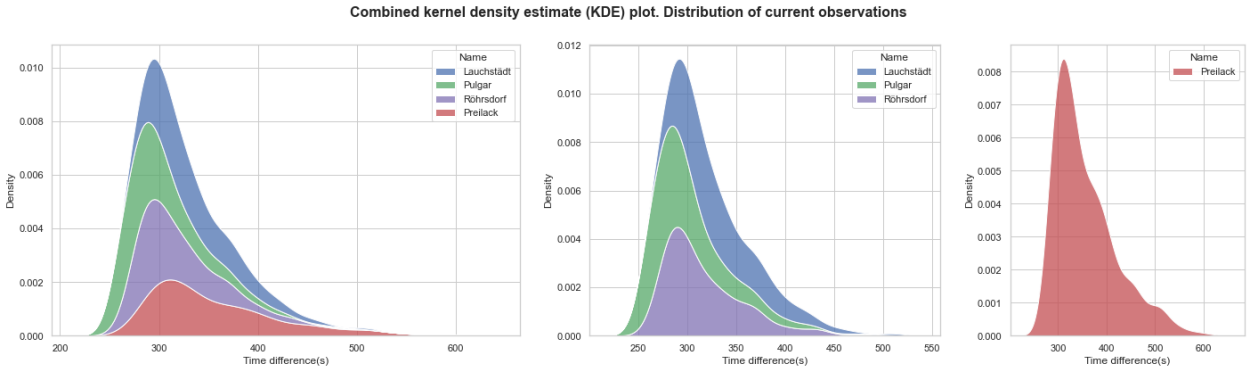

FIGURE 46 – COMBINED KDES GRAPH (CURRENT GRID)

According to the graph presented, a conclusion similar to the conclusion of the histograms' analysis is made. The greatest number of optimisation score values for Lauchstädt, Pulgar and Röhrsdorf falls on the interval from 250 to 350 seconds. For Preilack, the most frequent value of the optimisation score is between 300 and 400 seconds.
A similar pattern can be traced on the boxplot diagram in combination with the scatter plot (Figure 47).

FIGURE 47 – COMBINED BOXPLOTS GRAPH WITH SCATTERED OBSERVATIONS (CURRENT GRID)

The boxplots design principle is similar to KDE's. The categorical scatterplot shows the scatter of optimisation score values on the vertical axis respectively for each object under analysis. In the boxplot combined with the scatterplot, the intervals of the values of optimisation score are displayed as quartiles of the distribution, where each quartile corresponds to a certain percentage of observations. Observations outside the boxplot are considered as data outliers. According to the combined boxplots graph, the largest number of optimisations scores for each object is concentrated at the following time difference intervals:

- Lauchstädt: 305 – 360 seconds;
- Pulgar: 270 – 310 seconds;
- Röhrsdorf: 285 – 340 seconds;
- Preilack: 305 – 390 seconds.

This once again confirms the fact that the optimisation for Preilack takes longer than for other objects.

4.6.2 OPTIMISATION EVALUATION FOR FORECASTED GRID

The forecast estimation is represented by optimisation score values slightly higher than the values for the current grid. This is tracked by plotting of KDEs and combined boxplots with scatterplots for each object (Figure 48 and Figure 49).

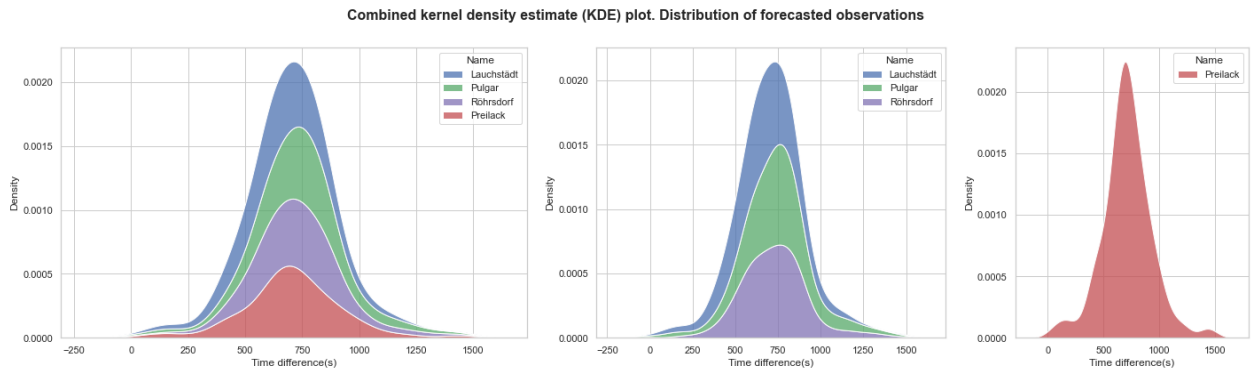

FIGURE 48 – COMBINED KDES GRAPH (FORECASTED GRID)

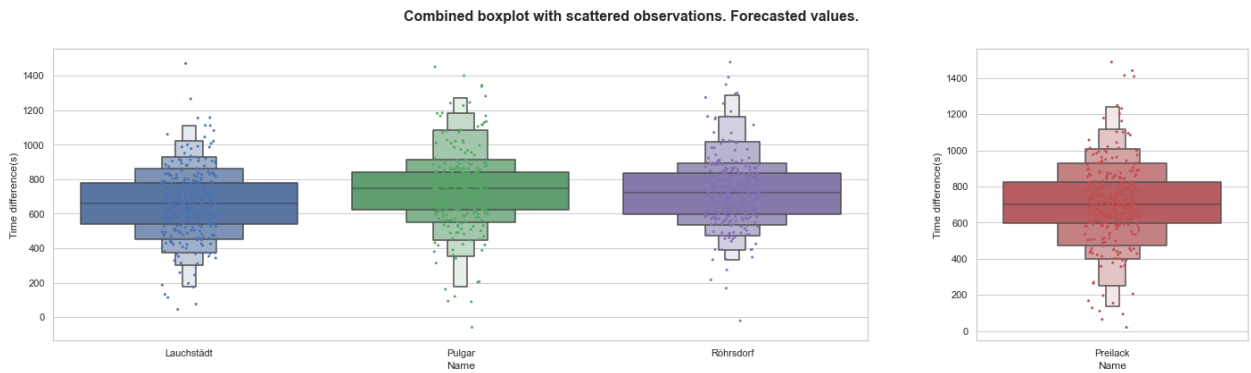

FIGURE 49 – COMBINED BOXPLOTS GRAPH WITH SCATTERED OBSERVATIONS (FORECASTED GRID)

The average variation of predicted values of forecast optimisation score is in the following range:

- Lauchstädt: 200 – 1100 seconds (largest number: 560 – 790 seconds);
- Pulgar: 200 – 1300 seconds (largest number: 610 – 840 seconds);
- Roehrsdorf: 350 – 1300 seconds (largest number: 600 – 830 seconds);
- Preilack: 140 – 1250 seconds (largest number: 600 – 810 seconds).

According to the evaluation of forecast optimisation data, the optimisation time difference is approximately the same for all the parts of the network – Lauchstädt, Pulgar, Röhrsdorf and Preilack. The forecast data is characterized by a wide distribution range especially in comparison to current network, which indicates the operation of additional data prediction modules as part of the optimiser and therefore requires more time for results obtaining. The processing time for predicted values is restricted by a frequency of forecast data coming, i.e. every 30 minutes. So, in accordance to the graphs built, the forecast data comes in and is optimised in a relatively stable way and easily meets the general 30-minute processing time threshold, but does not fit into the 5-minute limit for optimisation.

The combined weekly KDE distribution graphs for the current and forecasted optimisation score values (processing times) for each part of the network, respectively, are shown below for comparison (Figure 50, Figure 51, Figure 52 and Figure 53).

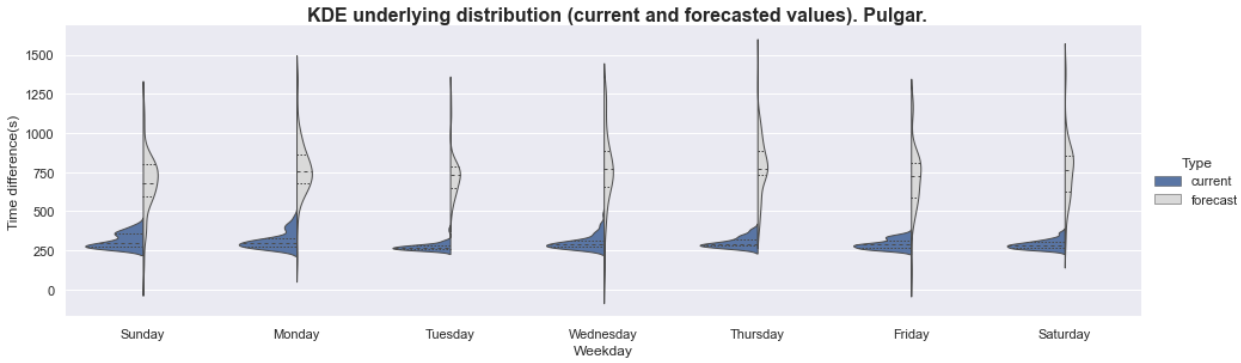

FIGURE 50 – KDES (CURRENT AND FORECASTED PROCESSING TIMES). OBJECT: PULGAR

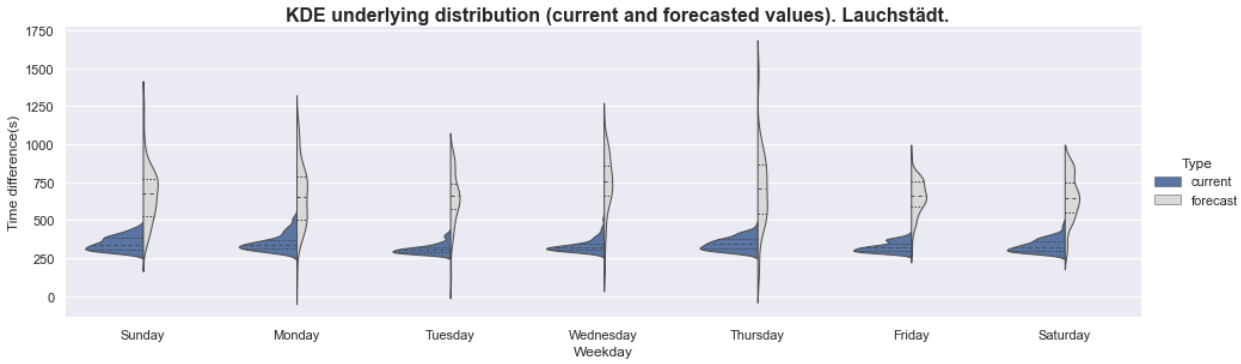

FIGURE 51 – KDES (CURRENT AND FORECASTED PROCESSING TIMES). OBJECT: LAUCHSTÄDT

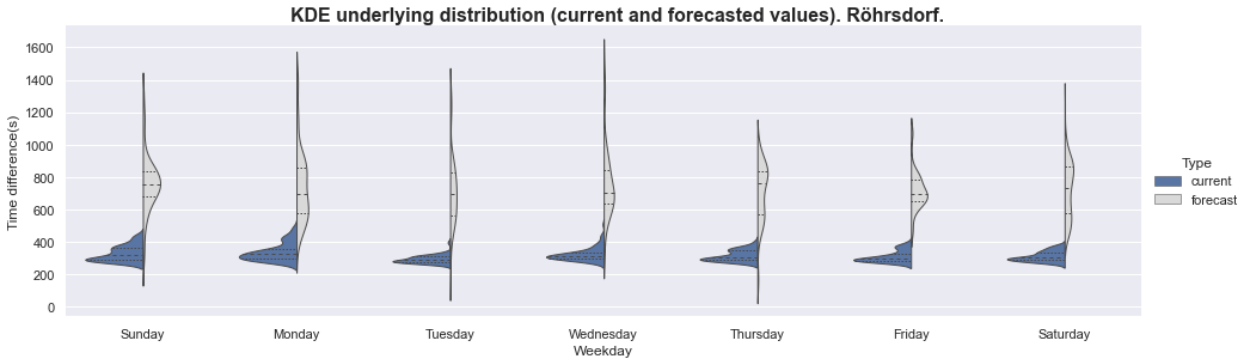

FIGURE 52 – KDES (CURRENT AND FORECASTED PROCESSING TIMES). OBJECT: RÖHRSDORF

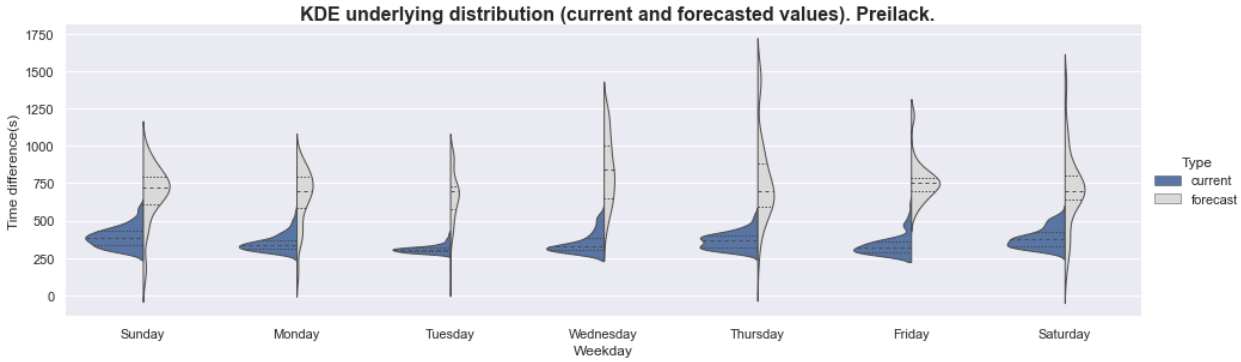

FIGURE 53 – KDES (CURRENT AND FORECASTED PROCESSING TIMES). OBJECT: PREILACK

According to the KDEs combined plots (for current and forecasted grid), the shift in the distribution of values for the current network relative to the values for the predicted network is visible. This reflects the operation of additional prediction modules in the optimiser, which are up during the processing of forecast values and hence take more time to produce results.

4.6.3 CONCLUSION

The statistical analysis of the processing times shows that the five-minute threshold is respected for the networks of Pulgar, Lauchstädt and Röhrsdorf. For Preilack, however, the large number of fluctuations and the overall optimisation score indicate the process to be in a critical state. Reasons behind this include failures in data transmission, complexity of interconnections and operation modes in the network models as well as data processing by the optimisation modules.

Possibilities to improve the optimiser performance could be to modify its calculation methods or to establish a stable data transfer to the optimiser with a reduction of delay between communication channels.

In the prediction mode of optimiser, the optimisation score is accordingly increased by the running time of the prediction modules, which leads to increase of processing time in general.

However, despite the critical level of optimisation scores for some parts of the network, the total processing times for the current and forecast networks are within the limits defined by the frequency of current time series and forecast data coming. As a result, the optimiser performs all calculations on time.

4.7 PQ-MAPS – FROM THE APPLICATION TO THE FIELD TESTS

Aiming to fulfil one of the main goals of the German Demonstration – enable a fast and reliable communication between TSO and DSO through optimisation mechanisms – the PQ-Maps has been tested by applying it to a real [16] 110 kV distribution network operated by MITNETZ STROM. Recalling its main goal, the new PQ-Maps tool (the original version was developed under the FP7 evolvDSO project [17]) intends to provide comprehensive insights to the TSO concerning the available flexibility margins at the interfaces with the DSO, even in the presence of meshed TSO-DSO connections. Therefore, the outcome should not only focus on the flexibility ranges estimation, but also on how they are redistributed throughout the different interfaces. Since such ability is dependent on the knowledge of how the transmission network behaves, the German demonstration was used as a real environment to test the

data-driven building process of transmission grid equivalents [16]. The aforementioned distribution network was specifically chosen to be aligned with the demonstration purposes. It is composed by three EHV/HV substations – Marke, Klostermansfeld and Lauchstädt – that together form closed loops. Thus, they allow to assess the accuracy of the developed methodology for estimating the power flows in meshed networks.

Following the contributions provided in [16] – algorithm description and first application tests – this deliverable describes all the steps that were carried to achieve a successful demonstration trial, namely:

- Integration of MITNETZ STROM internal systems with the developed methodologies;
- Data collection, processing and treatment procedures;
- Development of transmission network equivalent models and PQ-Maps execution;
- Demonstration process and critical analysis of the results;

4.7.1 DEMONSTRATION ARCHITECTURE

The demonstration trial was the result of several processes that were taken along the project lifetime. Although these processes were usually independently addressed, it was known from the beginning that, at a certain point in time, they would need to become interconnected. These processes are mainly divided in one-time process (off-line process) and the upon user request (online process). Therefore, the existence of an architecture to rule the demonstration processes was conceptualized from the very beginning - **Error! Reference source not found.**.

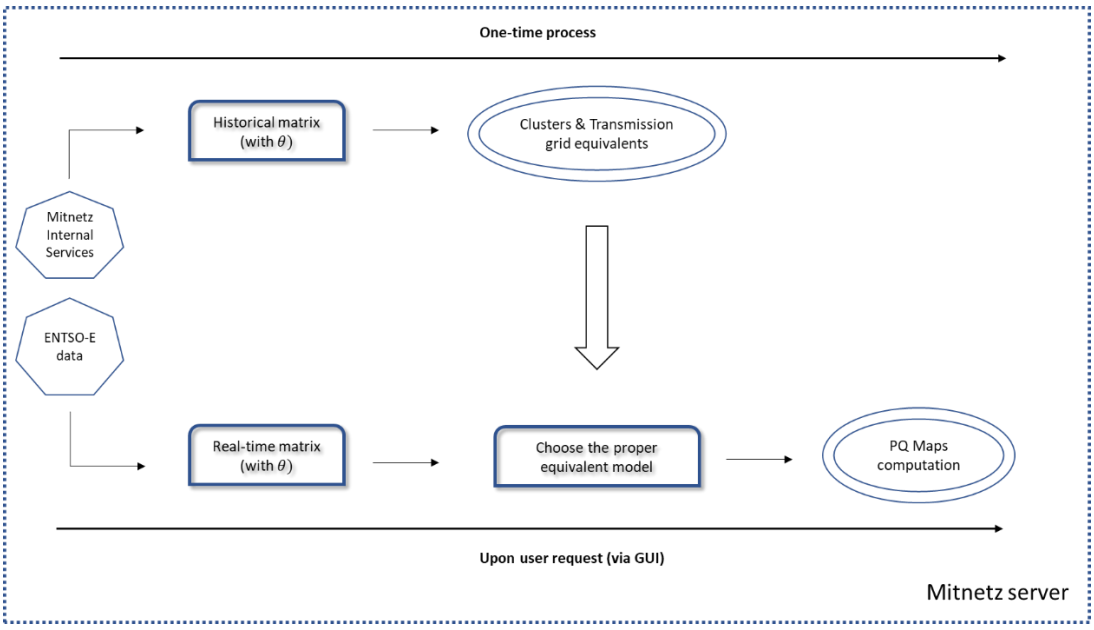

FIGURE 54 – DEMONSTRATION ARCHITECTURE

The whole architecture was built to comply with the requirements of the two central pieces – the equivalent construction process (one-time process) and the PQ-Maps computation (upon user request process). While the former is a one-time process that uses historical data to build transmission network equivalent models, the latter is triggered by the user through a dedicated GUI and uses the equivalent grids to better estimate the flexibility maps. Both pieces obviously rely on the availability of accurate input data that, in the case of a demonstration,

needs to be extracted from the field site. As such and considering the confidentiality issues associated with real-field data, a server access and a VPN connection was provided to INESC TEC. Thanks to it, the tools were deployed in a safe environment where all the necessary inputs could be shared between the INESC TEC tools and MITNETZ STROM internal services/databases. Focusing first on the development of the equivalent models, several data channels were enabled in order to provide the following historical information (with 1-year time horizon):

- CGMES files responsible to make available hourly network snapshots;
- Active (P) and Reactive (Q) power flow as well as Voltage magnitude (V) at each EHV/HV transformer (in a 15 min time step as basis);

The export of the CGMES files was necessary to complete the TSO-DSO interface variables. While P, Q and V at each EHV/HV substation were measured by MITNETZ STROM, the Voltage angle (θ) was not. This is a common situation since the widespread deployment of Phasor Measurement Units is not yet common. As such, power flow simulations were run in order to extract this missing variable. It was possible to run the metaheuristic responsible for fine tuning the electrical parameters of the equivalent model only with the complete set of these four variables. In addition, a request to ENTSO-E transparency platform was carried to access 1-year historical data for generation per production type and total demand in the 50Hertz (German TSO) control area. The data from 50Hertz allows for a better picture of the different operational scenarios that the transmission grid can face along the year. Based on it, a cluster procedure defines the optimal number of network equivalents that should be computed. The execution of the PQ-Maps is then dependent on choosing which network equivalent better fits with the real-time network status. To do so, CGMES files - exported on an hourly basis – were used to obtain the real-time P, Q and V. θ was once again obtained through a power flow execution.

Additionally, real-time data of the 50Hertz control area was accessed through the ENTSO-E transparency platform. With the real-time dataset completed, the appropriate network equivalent was chosen, attached to the 110 kV distribution network and the PQ-Maps computed.

Data from different sources are usually available with different formats and resolutions. Thus, every single data input had to be processed and treated before it could be used by the two main algorithms. First, a dedicated CGMES converter/processor was developed so that this standardized format could be recognized by the PQ-Maps internal structures. It is important to highlight that this converter was designed to comply with the entire CGMES standard so that any network that follows it (and not only the one used in the demonstration) can be parsed and analysed. Second, each variable that compose the historical/real-time datasets have different resolutions. Missing information (i.e., lack of inputs in specific timestamps) can also vary according to the source. Therefore, the developed data processing scripts focused on creating a single and coherent historical/real-time data matrix to be used by the main methodologies.

4.7.2 THE EQUIVALENT MODELS AND THE PQ-MAPS

The computation of reliable flexibility areas requires a transmission grid equivalent model to be then used by the PQ-Maps tool. More than focus on the technical characteristics of each step, which were already analysed in [16], the following paragraphs provides a detailed description of the different demonstration stages. **Error! Reference**

source not found. shows a flowchart of how a transmission grid equivalent model can be built based only on the available historical data. This also means that no access to the transmission grid topology is necessary.

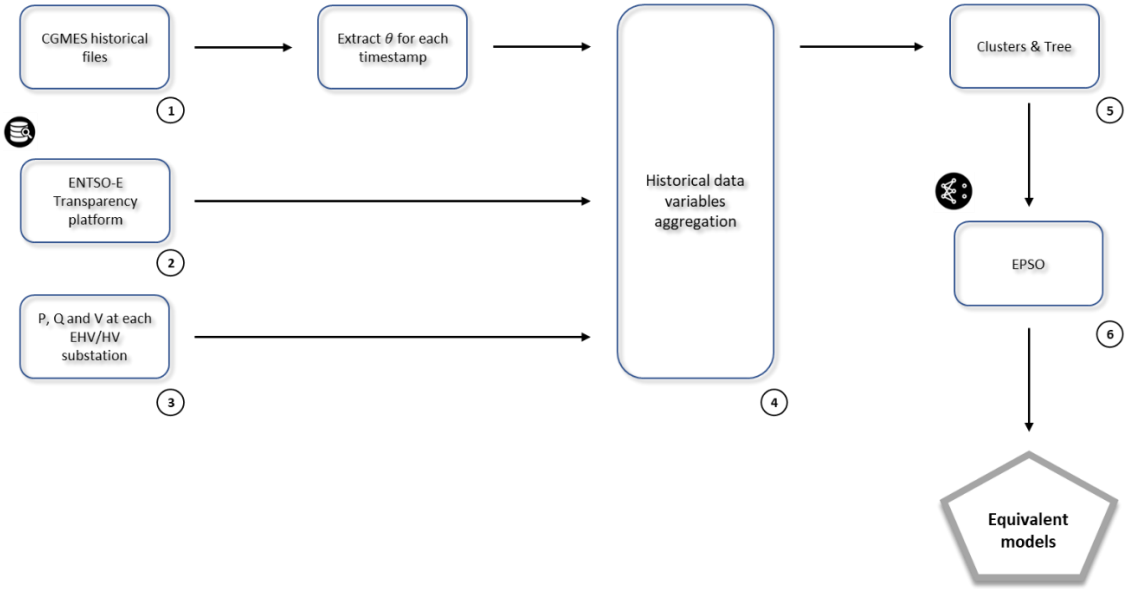

FIGURE 55 – DEFINING A TRANSMISSION GRID EQUIVALENT MODEL

The first three tasks have all the same goal: obtaining the historical data that will be the basis to construct the equivalent models. To do so, and as already mentioned, CGMES historical files from the previous operation year are parsed and used to compute the θ at each timestamp. Additionally, public data that illustrates how the 50Hertz transmission grid behaves along this same operation year is accessed via the ENTSO-E transparency platform. Together with the historical data of P, Q and V at each EHV/HV substation, these two data inputs are then analysed in process nº 4 – historical data variables aggregation. This process combines all the historical variables and defines a single and coherent historical matrix. Processes nº 5 and nº 6 represent the entry point of a more technical stage. Clustering & Tree are in fact two sub-processes that are carried within process nº 5. The first applies a *k*-means clustering technique that aims to partition the historical matrix into *k* mutually exclusive clusters. Prior to this sub-process, the matrix is refined by detecting and removing the existent outliers. The second sub-process uses the same historical matrix without outliers to construct a binary decision tree. This tree will allow the selection of a cluster to which a real-time operating scenario belongs. In other words, it will define which one of the *k* mutually exclusive clusters better fits with the real-time conditions. The reason for the clustering is that the transmission grid operation is dynamic and varies according to several characteristics of the network status (e.g., production type, total demand). As such, developing a unique transmission grid equivalent capable to encompass all the possible operating scenarios is a difficult task. The clustering procedure thus intends to define typical operation scenarios (i.e., *k* mutually exclusive clusters) and, consequently, the optimal number of network equivalents that should be developed.

Process nº 6 is the last one and is responsible for providing the main outcome – the transmission grid equivalent models. As described in [16], a metaheuristic called Evolutionary Particle Swarm Optimisation (EPSO) is used to fine-tune the line electrical parameters (resistance, reactance and susceptance) of a reduced network model.

Although being mostly a pre-defined model, the number of lines whose electrical parameters are optimised depends on the number of TSO-DSO connections. Since the demonstration site is composed by three EHV/HV substations, **Error! Reference source not found.** shows the equivalent model that was used in it.

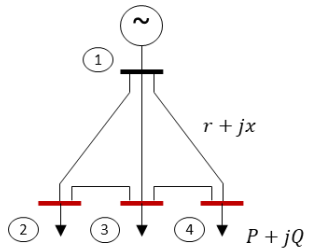

FIGURE 56 – EQUIVALENT NETWORK MODEL (TSO-DSO INTERFACE NODES IN RED)

The aim of the aforementioned fine-tuning is that the AC load flow results using the equivalent network are as close as possible to the ones observed in the target data (i.e., *P, Q, V and* θ of the historical matrix). Therefore, the active and reactive power flows in each substation ($P + jQ$) are imposed while a dedicated fitness function will be used in the optimization to minimize the *V* and θ squared error.

$$Fitness\ f. = 1 \times 10^{10} \sum_{t=1}^{T} \left(\sum_{i=1}^{CN} \left(V_i^{Equiv} - V_{i,t}\right)^2 + \sum_{i=1}^{CN-1} \left(\left(\theta_i^{Equiv} - \theta_{i+1}^{Equiv}\right) - \left(\theta_{i,t} - \theta_{i+1,t}\right) \right)^2 \right)$$

T illustrates the number of operating scenarios while *CN* the number of TSO-DSO connections. Thus, per each interface between the transmission and distribution grids, the employed metaheuristic intends to minimize the difference between $V\theta_{equiv}$ ($V\theta$ of the equivalent network) and the $V\theta$ (voltage magnitude and angle) of the available operating scenarios. Since the number of operating scenarios has a clear impact upon the EPSO computational time, their replacement by the centroid of each cluster represents an interesting possibility. This would reduce the target data to a single operating scenario per cluster and, consequently, the parameter tuning process would become much faster.

After the computation of the equivalent models, the PQ-Maps tool can be triggered by the user using the available GUI. Historical, real-time or forecasted PQ-Maps can be obtained. In the demonstration trial, the focus was given to the real-time assessment since forecasts were not available for all the input variables. These variables are the exact same ones with which the binary decision tree was trained. By inputting this real-time dataset into the pre-built decision tree, it is possible to attach the current operating scenario to one of the pre-defined equivalent models. That being said, *P, Q* and *V* at the interface nodes are obtained via the current CGMES while θ is once again computed through a power flow execution. The remaining real-time variables are requested to the ENTSO-E transparency platform. The joint work of these four processes provides the grid model (110 kV distribution network + equivalent model) that is used in the PQ-Maps tool. **Error! Reference source not found.** shows a schematic of how all these processes are interconnected.

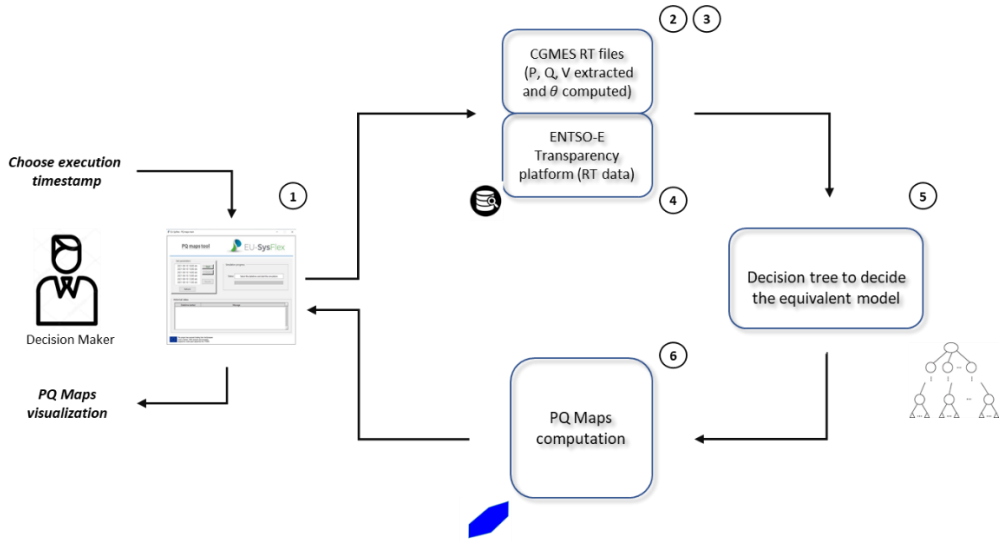

FIGURE 57 – ESTIMATING THE PQ-MAPS

The final process is the computation of the active and reactive power flow limits that can be achieved in each EHV/HV substation ($P_{DSO\rightarrow TSO}/Q_{DSO\rightarrow TSO}$) by exploiting the flexibility available in the 110 kV distribution grid and while complying with its technical constraints (e.g., voltage limits). In other words, the final process is the computation of the PQ-Maps. Their estimation is based on an optimisation process, whose objective function is iteratively updated by α and βso that the entire PQ-Maps perimeter can be explored.

$$\text{Objective Function} = \min\left(\alpha\, P_{DSO\rightarrow TSO} + \beta\, Q_{DSO\rightarrow TSO}\right)$$

The objective function geometrically represents a family of straight lines whose slope θ is defined by the coefficients α and β ($\tan\theta = -\alpha/\beta$). By varying θ, the intersection of the straight line with the feasible PQ plan changes and, as such, is possible to explore the entire perimeter of the PQ map as can be seen in Figure 58. The complete description of this methodology is available in [17]. Having the process finalized, the PQ-Maps can be displayed and analysed in the GUI.

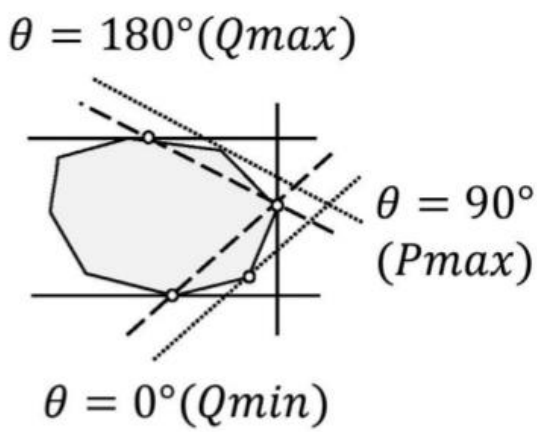

FIGURE 58 – PQ-MAPS ILLUSTRATION BASE ON THE TANGENT LINES

4.7.3 DEMONSTRATION AND CRITICAL ANALYSIS

The demonstration trials ran between the 26th July and the 6th August of 2021. This demonstration period was as expected divided in two main stages: the development of the transmission network equivalents and the execution of the PQ-Maps tool. Both stages relied on a meshed 110 kV distribution grid that was briefly presented in section 4.7. Marke, Klostermansfeld and Lauchstädt are the three EHV/HV substations that interconnect the transmission and distribution grids. Together they are composed by ten 380/110 kV on-load tap changers. Connected to the tertiary winding of some of these transformers there were also reactor banks. By being connected through both the transmission and distribution sides, Marke, Klostermansfeld and Lauchstädt compose the perfect site to test the effectiveness of the developed tools. Particularly, for testing the ability in estimating how the active and reactive power flows are redistributed per substation.

Focusing now on the equivalent models' development, the first task was to fill the historical matrix with all the necessary inputs (described in section **Error! Reference source not found.**). Therefore, data between 1st August 2020 and 29th June 2021 was retrieved from the different sources. Having the historical matrix completed, the clusters could then be computed and, consequently, the electrical parameters of the equivalent models were obtained (**Error! Reference source not found.**).

TABLE 4 – TRANSMISSION GRID EQUIVALENT MODELS

	Cluster 1	*Cluster 2*
R 1-2 (p.u.)	0.0443	0.0011
X 1-2 (p.u.)	0.0869	0.0479
B 1-2 (p.u.)	0.0221	1
R 1-3 (p.u.)	0.2353	0.0015
X 1-3 (p.u.)	0.001	0.5
B 1-3 (p.u.)	0.9879	1
R 1-4 (p.u.)	0.0327	0.0011
X 1-4 (p.u.)	0.0016	0.01
B 1-4 (p.u.)	1	1
R 2-3 (p.u.)	0.001	0.0447
X 2-3 (p.u.)	0.2418	0.5
B 2-3 (p.u.)	0.7396	1.9e-05
R 3-4 (p.u.)	0.0074	0.0074
X 3-4 (p.u.)	0.0372	0.0372
B 3-4 (p.u.)	0.0775	0.0775

The presented results show that two clusters were sufficient to represent the different operating conditions of the transmission grid between 1st August 2020 and 29th June 2021. Based on the centroid of each one of these clusters (i.e., reduced target data), the EPSO fine-tuned the line electrical parameters of two equivalent models. Numbers 1, 2, 3 and 4 in **Error! Reference source not found.** have the same meaning as in **Error! Reference source not**

found.. More specifically, bus number 1 is the reference while buses 2, 3 and 4 illustrate the TSO-DSO interfaces by the following order: Lauchstädt, Marke and Klostermansfeld. The reason why not exactly one year of historical data was used (approximately 11 months) is related with the existence of data gaps in some sources. Having accomplished the purpose of the first stage – transmission grid equivalent models – the user was able to start testing the PQ-Maps tool. As already mentioned and as shown in Figure 59, a dedicated GUI was made available to facilitate the interaction between the user and the tool. Through it, the user can trigger the PQ-Maps tool for a real-time or historical analysis (i.e., compute the PQ-Maps for previous timestamps). Additionally, after executing the tool, the flexibility areas can be displayed in the GUI by clicking on the "Results" button.

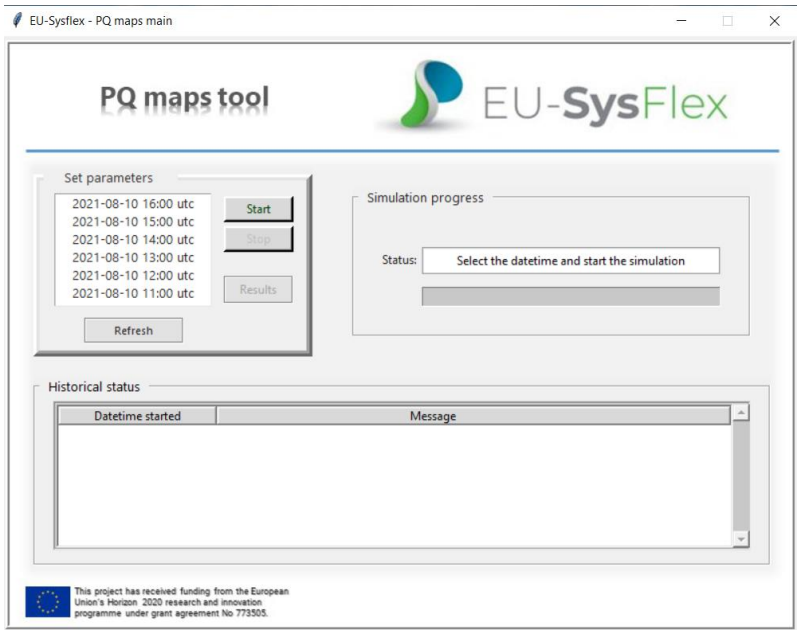

FIGURE 59 – PQ-MAPS GUI

All the processes detailed in **Error! Reference source not found.** are controlled and managed by the front-end application in Figure 59. In case any error occurs during the processes' execution, the GUI presents an error message as exemplified by Figure 60. Moreover, all the logs as well as the inputs/outputs of a particular simulation are stored in a dedicated folder. Thus, the user always keeps track of prior records and has the possibility to replicate them.

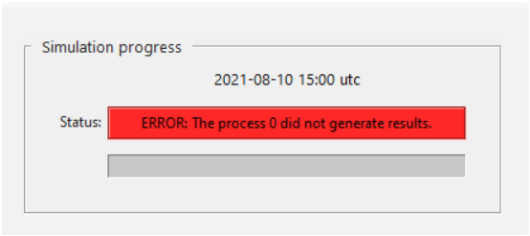

FIGURE 60 – ERROR MESSAGE DISPLAYED IN THE GUI

Before going into the results analysis, it is of utmost importance to detail which resources available on the distribution grid were considered as flexible. Without them, the PQ-Maps would show no flexibility margins at the TSO-DSO interconnections. The following list thus shows the so-called flexibility resources:

- *Renewable Energy Sources (RES) connected to the MITNETZ STROM distribution grid*
  - Active power curtailment: $-10\% * P_{actual} \leq P_{flex} \leq 0$
  - Reactive power support: $-32\% * P_{actual} \leq Q_{flex} \leq 41\% * P_{actual}$ (if $\frac{P_{actual}}{P_{inst}} \geq 20\%$)
- *Demand Resources connected to the MITNETZ STROM distribution grid*
  - Active power curtailment/increase: $-5\% * P_{actual} \leq P_{flex} \leq 5\% * P_{actual}$
- *Reactor banks connected at the EHV/HV substations:*
  - Reactive power support (inductive): $Q_{flex} \in \{-Q_{nom}; 0\}$

The definition of these flexibility bands did not follow any specific regulation or regulatory requirement. This option had the purpose to not constrain the PQ-Maps tool to a specific type of flexibility and, as such, shows its effectiveness independently of the flexible resources type. Nevertheless, attention was given to the resources that are expected to become active flexibility providers in the coming years. Exceptions to this were the RES reactive power bands, which were defined according with typical Q capability curves.

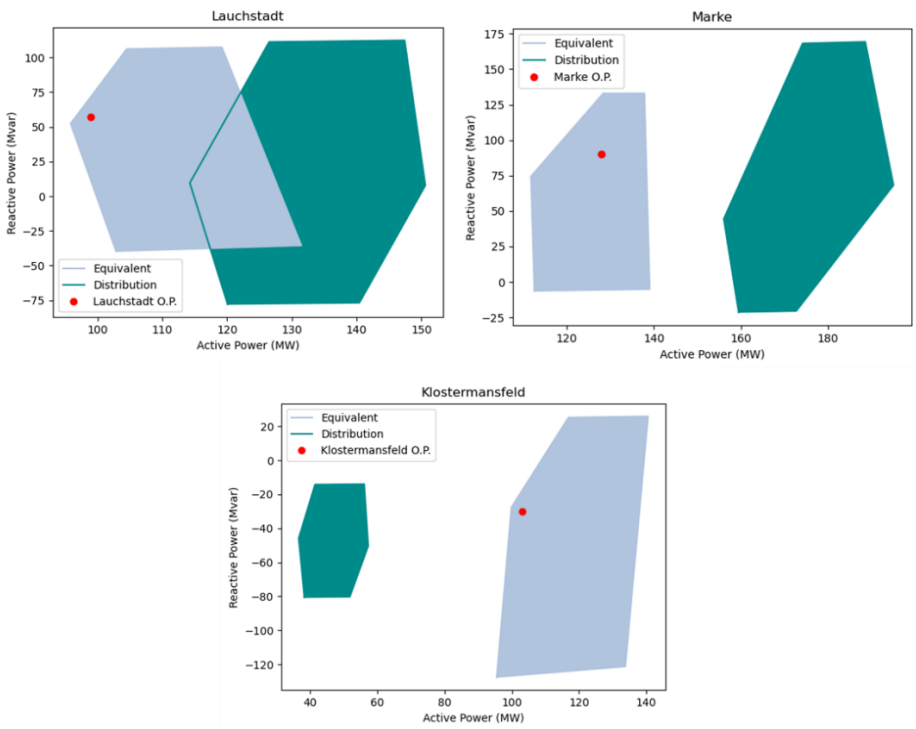

FIGURE 61 – PQ-MAPS RESULTS (TEST-CASE 1)

From the several test cases that were performed within the demonstration period, two of them will be highlighted for different reasons in this deliverable. One of them will graphically show the importance of computing the PQ-Maps departing from accurate equivalent models of the transmission grid while the other will lead to a critical

analysis on how the algorithm is sensitive to the input data quality. Figure 61 shows the PQ-Maps obtained (per substation) for test-case nº1, which corresponds to the following timestamp: 2021-07-30T04:00:00Z UTC.

Two different PQ-Maps are presented for each EHV/HV substation. The ones in green result in absence of knowledge of how the transmission grid is operating. On the other hand, the grey flexibility areas are associated with the availability of fine-tuned equivalent models of the transmission network. As already mentioned, the three TSO-DSO interfaces are electrically connected through both the transmission and distribution sides. This means that the entire 110 kV distribution grid can be fed through any of these three connections, as long as the technical limits are respected. Having this in mind, a new question arises: *how to estimate the P and Q quantities that will flow per each TSO-DSO interface?* This is only possible if a complete knowledge of how the grid is operating is available (and not only concerning the distribution side). Since confidentiality issues could block the easiest path to acquire this knowledge of a transmission network model, an equivalent of it needs to be developed. As clearly shown in Figure 61, the absence of this equivalent leads to a power flow redistribution that is not realistic. The red dot available for each substation is what truly validates the methodology since it represents the P and Q real-time measurements extracted from the CGMES files. Important also to refer that prior to the PQ-Maps computation, the appropriate network equivalent was chosen. To do so, the real-time matrix was built, the decision tree used and the final result obtained: equivalent model of cluster nº2 in **Error! Reference source not found.**.

A similar procedure was carried for test-case nº2 (2021-07-30T22:00:00Z UTC) and the outcome was the same: the chosen equivalent model was the one developed using the centroid of cluster nº2 (**Error! Reference source not found.**). The 110 kV distribution network was then connected to this reduced model and the PQ-Maps computed as can be seen in Figure 62.

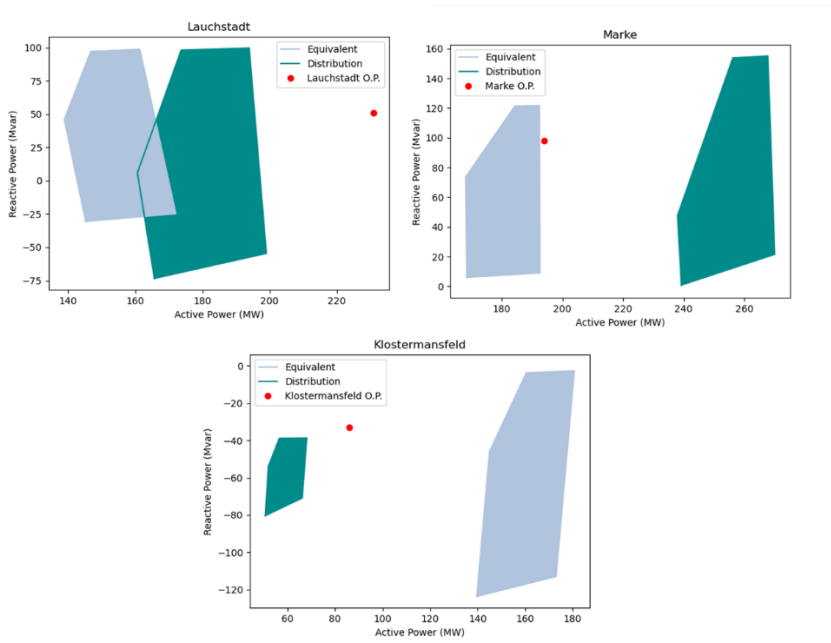

FIGURE 62 – PQ-MAPS RESULTS (TEST-CASE 2)

Although the same techniques were followed, test-case nº2 results were not according the expectations. The green and grey areas have the exact same meaning as in test-case nº1, which tells us that the fine-tuned equivalent model

was not able to illustrate the transmission network behaviour in this specific timestamp. In other words, the representativeness provided by the pre-defined clusters was not enough to characterize the current operating scenario in the transmission grid. This link between the clusters definition and the inconsistencies observed in Figure 62 needs to be well explained since theoretically any other process could have contributed to the aforementioned problems. In fact, in all the different test cases that were performed, a similar pattern was observed: the equivalent model linked with cluster nº2 was always chosen. Moreover, this model always had a similar impact upon the power flow redistribution per each TSO-DSO interface. These observations lead to something that was already discussed in section **Error! Reference source not found.**: a single equivalent model is not capable to represent all the different operating conditions that an electrical network can face. This is the reason why the equivalent model related with cluster nº2 provided accurate results only in some cases. Important to refer that the equivalent model corresponding to cluster nº1 would lead to even worse results since this cluster intends to illustrate other class of operating points. Having identified the demonstration stage where the problems began, now it is time to understand why other clusters were not defined thus allowing representing other groups of operating points. The root-cause is in the quality of the data inputs used to build the historical matrix. Although mitigation actions were carried (e.g., calculation of θ), they were not enough to overcome the noise brought by some of the data sources:

- Data obtained from ENTSO-E concerns to the entire 50 Hz control area. Such area encompasses not only the three TSO-DSO interfaces of the demonstration site;
- The historical P, Q and V values at each EHV/HV transformer are 15 minutes average values. However, the computation of θ uses the P, Q and V values available on the CGMES files, which are instantaneous values. Therefore, the historical matrix is composed by P, Q and V values that do not perfectly match with the obtained $\theta's$;
- The 110 kV distribution grid that was used to calculate $\theta's$ also had some calibration problems: P and Q values for each generator/load were not always available. In such cases, measurements were gathered from upstream transformers/transmission lines and then allocated to the respective generators/loads. In the absence of a dedicated algorithm to perform this allocation, a set of heuristic rules were defined, which naturally introduced some errors.

The critical analysis to the obtained results is one of the most important contributions of this deliverable. At the same time that it became clear the importance of the transmission grid equivalent models, it was also visible the impact of data quality in their accuracy. By not relying in the transmission grid topology, this methodology is highly sensitive to the quality of the historical matrix.

The assessment of the demonstration tests effectiveness was carried by inspecting the position of the substations' operating point in the PQ plan. If these operating points were encompassed by the fine-tuned flexibility areas (i.e., the ones computed considering the optimised equivalent model), the test trial was considered as successful. Turning this assessment into a numerical analysis, **Error! Reference source not found.** shows the defined Key Performance Indicators (KPI).

TABLE 5 – KEY PERFORMANCE INDICATOR 1

		KPI
TEST-CASE Nº1	FINE-TUNED MODEL	μ = 2.6s σ = 0.56
	NON-OPTIMISED MODEL	μ = 3s σ = 0.72
TEST-CASE Nº2	FINE-TUNED MODEL	μ = 3.5s σ = 0.85
	NON-OPTIMISED MODEL	μ = 4s σ = 1.2

KPI nº1 is focused on the computational effort that is necessary to execute the PQ-Maps methodology. In order to verify the computation effort, each test case was simulated twenty times and thus the mean (μ) and standard deviation (σ) were calculated. In the fine-tuned model, the simulation of PQ-Maps is done using transmission equivalent data (**Error! Reference source not found.**). In the non-optimised model, the simulation of PQ-Maps is done using fixed values for R, X and B (all equal to 0.0001) in the transmission equivalent model (**Error! Reference source not found.**).

A different analysis would be possible if the real transmission network model was available. In that case, the PQ-Maps would be computed considering the complete knowledge of the transmission grid and compared against the ones obtained with the equivalent model. By doing so, an even better picture of how the equivalent grid is capable to illustrate the real scenario would be possible. Additionally, and although for the majority of the German demonstration KPI defined in [7] it is not possible to establish a quantifiable link with the PQ-Maps, there is a correlation that cannot be neglected. Particularly in the KPIs associated with meeting TSO needs, the higher observability promoted by the PQ-Maps works as a facilitator to fulfil such objectives.

4.8 AUTOMATED TOOL

A main objective of the German demonstration was to develop a tool integrated in the grid control centre to support the operating staff. The reasoning is to reduce complexity in decision making to secure a reliable energy supply. To achieve this objective, the approach of the German demonstration is to automate the process from set point proposal to communicating these set points to the respective power plants. The proposal of set points is the result of the optimisation. These results will be sent to the grid control centre via XML format and the grid control centre will execute these proposals with existing functionalities.

In order to show the benefits of automated set point processing, a simulation of a grid region of MITNETZ STROM was used. In this simulation, a line loading violation in the overlaying transmission grid was assumed and a correlated demand on active power reduction on a certain GCP was communicated by the TSO.

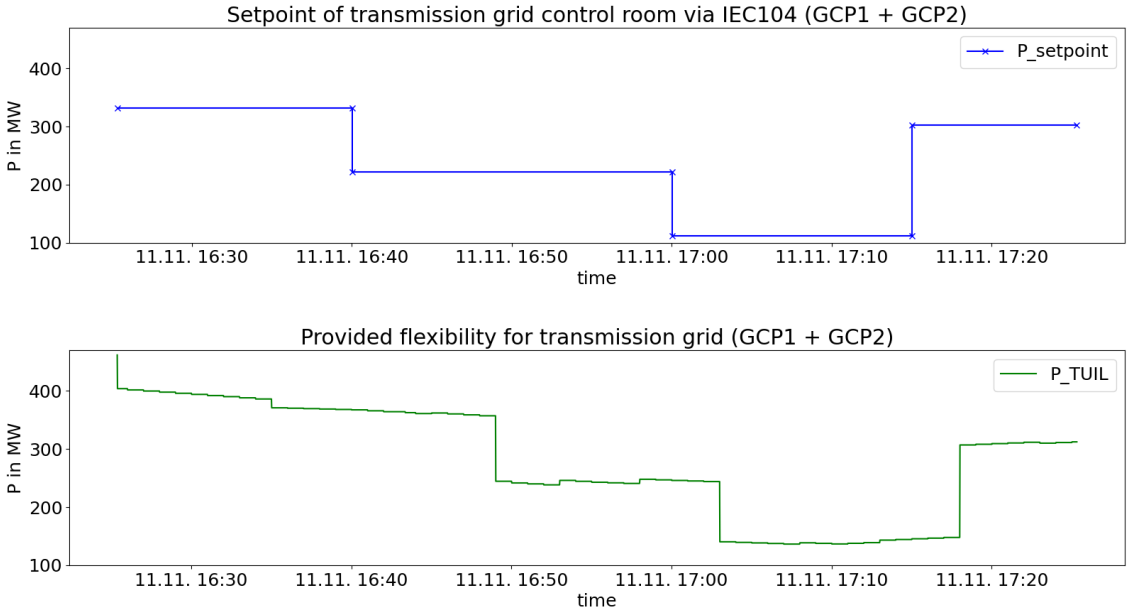

FIGURE 63: AUTOMATED ACTIVE POWER SET POINT PROCESSING IN A SIMULATION
UPPER PANEL SHOWS SET POINTS SENT BY THE TSO, LOWER PANEL SHOES THE RESULTING ACTIVE POWER FLOW OVER BOTH GRID CONNECTION POINTS.

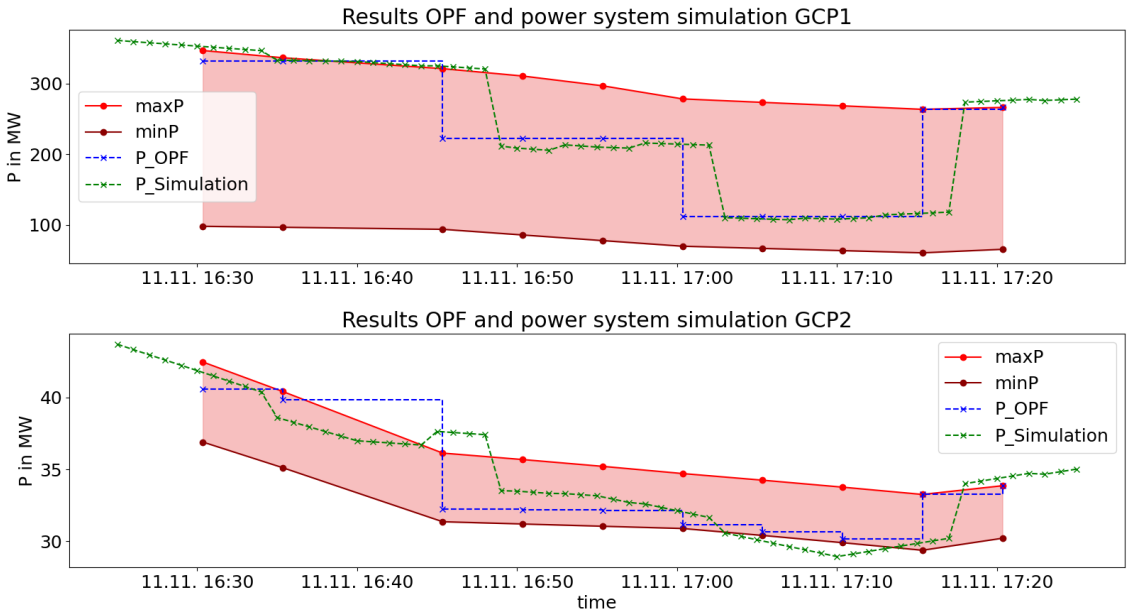

FIGURE 64: AUTOMATED ACTIVE POWER SET POINT PROCESSING IN A SIMULATION
EFFECTS OF NEW SET POINTS IN THE GRID SIMULATION

In Figure 63, sent set points on active power for a grid connection point (GCP1) from TSO are shown in the upper panel. These set points are automatically used as input for the optimisation. As one can see, there were four different set points given over the time of the simulation. In the lower panel, the resulting active power flow over two grid connection points are shown.

In Figure 64, the possible active power flexibility band is shown in the red shaded are, as well as the current active power at the GCP in green and computed expected active power at GCP determined by the optimisation algorithm. One can see that within a few minutes, the given set point from the TSO is processed by the optimisation (blue line) and the resulting set points for DER are automatically sent into the simulation and are processed by the simulated DERs. A few minutes later, all DER set points are processed and the effect is visible in the grid simulation (green line). In the lower panel, the related changes and effects at GCP2 are also visualized. Due to the overall changing grid state, at some moments in time, the new resulting active power flow over GCP2 can exceed the pre-computed flexibility band.

An automated processing of set points is of great advantage in comparison to a manual processing. Depending on the number of DERs in a certain grid region, the individual set points for each participating DER can be numerous. On a rough estimate, between 5 and 20 DERs are involved in such flexibility demands. In a previous German research project, SysDL2.0 [18], a similar test was done and the set points for the DER were manually processed by the grid operator. The result was that each DER set point was transmitted to the DERs with a delay of about 20-30 seconds between each other and hence the duration of the overall process was significantly longer. In addition, the grid went through more intermediate states before reaching its new set point. Nevertheless, most importantly, the stress inflicted on the grid operator indicated, that an automated process is necessary.

5. CONCLUSION

The German demonstration within the work package 6 of EU-SysFlex demonstrated the utilisation of flexibility services from resources connected to the distribution grid. The German demonstration also included functionalities to make distribution grid connected flexibility available for the TSO without jeopardising the DSO grid operation.

Within the German demonstration, two tools have been developed to help scheduling preventive and corrective measures in congestion management and voltage control. One tool, the IEE.NetOpt, was developed by Fraunhofer IEE and tested under operational conditions in the grid control centre of the DSO MITNETZ STROM. This tool supports the decision-making process of the operator in preventing congestions and voltage issues via a security constrained optimal power flow calculation. IEE.NetOpt uses grid topology data and the related data in CIM-CGMES format together with schedules and forecasts of infeed and consumption to predict contingencies up to 48 h ahead and proposes measures to ease them. The tool is in line with the requirements of today's regulatory framework. That means a function is integrated that computes and generates segregated lists of available active and reactive power flexibilities at the DSO-TSO interface (see Figure 65) as well as can handle aggregated set points at these interfaces (see Figure 66) in order to realize those using decentralized generating units. With this, the TSO has all the information needed as input for its own congestion management to calculate the best option to prevent contingencies with the activation of flexibility in the distribution grid without jeopardizing with distribution grid stability. Additionally, the combination of active and reactive power management allows a more efficient use of flexibilities.

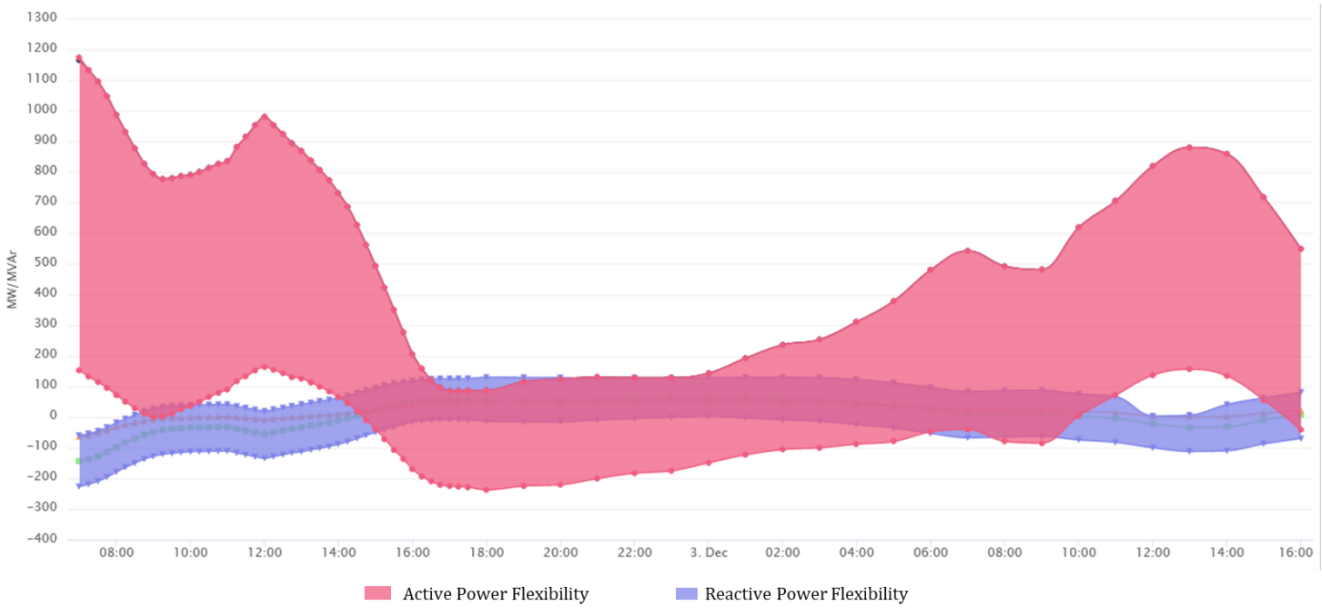

FIGURE 65 – FLEXIBILITY POTENTIAL

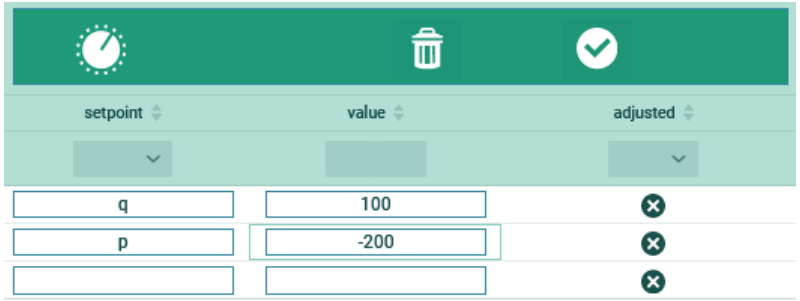

FIGURE 66 – USER INTERFACE TO INSERT SET POINTS

The second tool of the German demonstration focuses even stronger on the interdependencies of active and reactive power management at the DSO-TSO interfaces. The PQ-Maps tool was developed by INESC TEC and tested with a partial grid of MITNETZ STROM. This tool predicts the joint active and reactive power ranges that can be exchanged at the DSO-TSO interfaces while using the available flexibility resources connected to the distribution network without compromising its operation (see **Error! Reference source not found.**). The information presented by PQ-Maps provides a significant support for planning and operational domains. Thus, PQ-Maps enhances the accuracy in the definition of contractual values of electrical energy exchange between transmission and distribution systems. Furthermore, PQ-Maps helps the DSO to avoid penalizations due to possible violations of power exchange defined by the TSO, although that is not the case in the area operated by MITNETZ STROM. Moreover, if the TSO has several DSO grid interconnection substations the tool performs the PQ-Maps for each interconnection enabling how the active and reactive power are redistributed throughout the DSO-TSO interconnections. Currently, the tool cannot be used in daily operation due to the strong aggregation, because the German regulation requires for schedule-based congestion management (redispatch) the segregated information of each to be activated flexibility on grid connection point level. This needed function is not integrated in PQ-Maps yet.

The approach of PQ-Maps compared to IEE.NetOpt is the usage of historical data instead or the need of the transmission grid topology data. Both approaches show good results in accuracy. It is shown that the better the input accuracy the better the results. If the DSO gets the data of the observability area of the transmission grid, IEE.NetOpt works with high accuracy. On the other hand, the disclosing information of the transmission grid data to DSO could give rise to confidentiality issues. If this data is not available, IEE.NetOpt only can secure accuracy due to the process approach in the German demonstration of executing every 15 minutes an optimisation with updated input. PQ-Maps on the other hand uses equivalents of the transmission grid created from historical data. With this approach, the data from the observability area of the transmission grid is not needed, but the risk of low accuracy is higher if the historical data does not represent the transmission behaviour. If not enough historical data is available from the transmission grid, the resulting ranges of active and reactive powers at the DSO-TSO boundaries are not reliable. Taking this into account, the advantage of IEE.NetOpt in this case is that congestion management and voltage control in distribution grid are still manageable.

In Figure 67, different properties of power plants are shown in the developed user interface of IEE.NetOpt. In the column “opt”, the optimised set points are shown, in the column “actual” the active set point, in the columns “min” and “max” the flexibility limits of each power plant and in the column “diff” the deviation between active and optimised set point.

opt	diff	actual	min	max
21.921	23.935999	-2.015	-19.14	23.78
10.66	13.166	-2.506	-8.58	10.66
9.644	8.254	1.39	-8.25	10.25
5.274	8.045	-2.771	-13.86	17.22
5.972	6.399	-0.427	-5.94	7.38
6.128	5.515	0.613	-4.932	6.128
5.502	3.56	1.942	-4.428	5.502
3.233	2.894	0.339	-2.602	3.233
-4.334	2.481	-1.853	0.192	-4.634

FIGURE 67 – SEGREGATED SET POINTS

Several simulations and field test were carried out and they not only have proven the feasibility of the approach of the German demonstration, but have also shown the benefits of DSO-TSO coordination and combined optimisation of active and reactive power flexibilities.

5.1 KEY MESSAGES GERMAN DEMONSTRATION

Based on the results and lessons learnt during the development, field test and analysis of the results of the demonstrator, 6 main key messages are drawn:

The coordination of flexibility providing System Operator (SO) and flexibility demanding SO is key for an efficient use of flexibilities.

The DSO must optimise the distribution network both for its own requirements and to satisfy the requests coming from the TSO, exploiting new SCADA functionalities and an advanced Smart Grids infrastructure. For an efficient and effective DSO/TSO coordination, the process for flexibility selection and activation shall be automated as much as possible. Accessing flexibilities from another grid without coordination results in uncertainties and jeopardises with grid operation and therefore with the reliability of supply. Forecasting, optimisation, control logics as well as reliable communication systems are needed to enable the utilization of assets in the flexibility markets.

The DSO needs to be involved in the operational planning and in the procurement of congestion management and voltage control services, given that most of the flexibility resources are connected to the distribution grid. Therefore, the role of the DSO is evolving more and more to an active system operator in all voltage levels. The DSO shall be given the room for action to fulfil its responsibilities as an active system operator.

The tools of the German demonstration as described in this report support DSO-TSO coordination in providing information about available flexibility at DSO-TSO interfaces in day-ahead and intraday timeframe. This information brings benefit only if a process is defined to exchange the information in an updated/continuous way. The defined process in the German demonstration is based on the existing process of redispatch. Due to similar information needed for active and reactive power management, analogical processes for redispatch and voltage control were described. There is a difference in time to update the information between day-ahead and intraday. The guiding

principle the closer to real time the more accurate the information needs to be is taken into account. With this processes a DSO-TSO coordination for preventive and corrective measures in active and reactive power management is executable without risking reliable, stable and efficient supply. Another principle of the tested and proven coordination scheme is the shared responsibility for the whole system with the respective concentration on its own grid. This design of coordination scheme enhances the resiliency in strengthen the liability according to EU Directive 2019/944. In addition, the approach allows the reduction of complexity in data exchange due to the introduced principles of data thrift that includes a feasibility of strong aggregation level in data excvhange.

Efficient Schedule-based management of active and reactive power for redispatch and voltage control is feasible.

The developed grid optimisation and processes (see Figure 10, Figure 11 and Figure 12) allow schedule-based congestion management including balancing of adjusted infeed and load. This reduces the amount of needed frequency control reserve and allows the procurement of cost efficient flexibilities. For efficient congestion management and voltage control, the crucial factor is the knowledge of sensitivity of the flexibilities to ease the need, means the impact on the grid in case of activation. Although regulation for reactive power management and active power management is different, the benefits for congestion management and voltage control are similar. To summarise it, the German demonstration has shown its advantages for a more efficient operational planning for DSO and TSO.

The accuracy of forecast is the most important factor for reliable prediction of network states.

The schedule-based process, as used in the German demonstration and described in chapter 3, starts with a forecast horizon of approximately 36 h (see Figure 10). As shown in chapter 4.1 and chapter 4.2, the deviation of forecast is higher than of state estimation. Therefore and because it is a direct input into the schedule-based congestion management and voltage control, the accuracy of forecast determines the accuracy of results of optimisation. To produce trustable results, trustable forecast is key.

The prediction of reactive power deviates more than active power.

As shown in chapter 4.2, the stronger non-linearity of reactive power results in higher deviation. Together with deviation from forecasting, the horizon of schedule-based voltage control has to be chosen carefully. It also influences the achievable efficiency of preventive redispatch. Because of the interdependencies of active and reactive power management, grid operation needs to consider these uncertainties.

The complexity for grid operators can be reduced by German demonstration's Decision Support Tools.

Today's low observability of the distributed generation plants behaviour in the distribution system hinders an efficient integration of renewable energies in system operation. An increased system observability in distribution grids shall be achieved. The tools of the German demonstration improve the observability in the high voltage distribution grid and partly in the underlying voltage levels (see Figure 65).

In addition to that, in autumn 2018 a voltage-threatening event happened in the German Demonstration's area creating voltage violations. The voltage drop that happened on October 24th 2018 can be seen in Figure 68. The figure displays 8 hours on the x-axis and the voltage in kV of the EHV grid on the y-axis with the lower limit of acceptable voltage range of 390 kV. The voltage drop could only be stopped due to emergency measures of active power curtailment of 1 GW in the grid of MITNETZ STROM and additional active power in the grid of neighbouring DSOs. It was caused by the large amount of energy transported from north to south and the failure of reactive power support in the transmission grid. Further small voltage drop would have lead to a blackout due to the dependency of transported energy, voltage and reactive power need. The occurrence of events like this proves the need for new solutions like innovative voltage control across DSOs' and TSOs' individual borders.

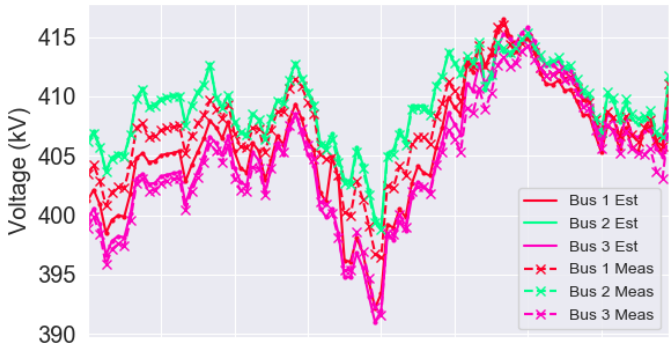

FIGURE 68 – VOLTAGE PROFILE DURING CRITICAL EVENT IN GERMANY

As shown in the German demonstration, support from automated tools is feasible to reduce the complexity of decision making in grid operation. Additionally the reduction of complexity was achieved due to the data thrift principle that the data exchange should be limited as far as possible and executed with strong aggregated information.

The efficiency of grid operation can be increased by approximately 5 %.

The results of the German demonstration prove an enlarged amount of possibilities and the increased efficiency of flexibility usage. Depending on the available flexibility, German demonstration has shown up to 9 % higher efficiency (average around 5 %). Due to these reduced grid losses, costs for operating the innovative tools of the German demonstration are compensated. Therefore, grid user could participate in enhanced efficiency of grid by minimised grid connection fees.

5.2 OUTLOOK

Results of the German demonstration reveal further challenges that should be tackled. These challenges include existing barriers in regulation that hinder data thrift principles in TSO-DSO coordination as not only the results of the PQ-Maps tool has shown, but also the discussions with the TSO in developing the schedule-based congestion management and voltage control processes. Another regulatory limit is the exclusion of consumer flexibilities from the redispatch process. The reasoning behind this challenge is the heterogeneity of consumer and the resulting

complexity of regulated price building of flexibility products. With adopting a market approach, this challenge could be tackled.

Other challenges are on the technical side like the accuracy of forecast, the integration of uncertainties in grid operation and further co-optimisation of active and reactive power management. Due to the variety of voltage control schemes (e.g. Q(P) curve, Q(V) curve, Q set point) and the complexity of integrating these schemes into the co-optimisation, not all potential flexibility facilitations could be included in the German demonstration. Therefore, future developments and innovation should tackle the technical complexities to create most valuable support for decision making in grid control centre to ensure high reliability of supply.

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