TwinEU digital twinning for DER integration

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Document Authors	
Vladan Ristic (SCBG)	Nikolay Chavdarov (ESO EAD)
Nikolay Palov (SCBG)	Pencho Zlatev (SETECHCO)
Yasen Todorov (EDG West)	Angel Markov (SETECHCO)
Milena Kovacheva (EDG West)	Ralitsa Rumenova (EE)

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Responsible Partner	SCBG, SETECHCO, EDG West, ESO EAD, EE
Checked by WP leader	Nikolaos E. Koltsaklis (UPRC), 28.11.2025
Verified by the appointed Reviewers	Vasiliki Kontargyri (UoA), 15.11.2025 Ilias Zafeiropoulos (UBE), 24.11.2025
Approved by Project Coordinator	Padraic McKeever (Fraunhofer), 02.12.2025

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List of Abbreviations and Acronyms

Acronym	Meaning
AI	Artificial Intelligence
ANN	Artificial Neural Network
BESS	Battery Energy Storage System
BUC	Business Use Case
DSO	Distribution System Operator
DT	Digital Twin
EHV	Extra High Voltage
EV	Electric Vehicle
FSP	Flexibility Service Provider
HV	High Voltage
KPI	Key Performance Indicator
LV	Low Voltage
MAPE	Mean Average Percentage Error
MV	Medium Voltage
NTC	Net Transfer Capacity
OHL	Overhead Line
PoI	Point of Interest
ReLU	Rectified Linear Unit
RES	Renewable Energy Source
RH	Relative Humidity
SO	System Operator
SPP	Solar Power Plant
SS	Substation
SUC	System Use Case
SWR	Short-wave Radiation
TOTCL	Total Clearness
TSO	Transmission System Operator
UC	Use Case
WP	Work Package
WPP	Wind Power Plant

Executive Summary

This report represents the main deliverable of the Bulgarian pilot within Work Package 7 of the TwinEU project and includes five partners in its actions – ESO EAD, EDS West, Entra Energy, SCBG, and SETECHCO. Among these partners, there is a TSO in charge of the entire Bulgarian transmission system and the DSO which operates the Western part of the Bulgarian distribution system. This ensured that the solutions developed in the scope of this pilot were indeed the ones that would be of interest for the system operators, as the most likely end users once solutions reach the sufficient level of maturity.

For the goals set before the Bulgarian pilot to be reached, partners have developed several Digital Twins, such as the EHV-HV Digital Twin (dealing with the transmission grid), MV Digital Twin (covering the distribution grid) and cross-border energy exchange Digital Twin (simulating the energy exchanges between Bulgarian system and systems around it). These were developed in the same software tools that are commonly used in the modelling process (PSS/E for grid and ANTARES for market), with the main enhancement of the Digital Twins, compared to the usual simulation models, being the fact that they have been fully automated by using the made-for-purpose scripts and paired with the Artificial Neural Networks (ANNs) for the forecasting of relevant system parameters. The forecasts done by the ANNs have proven to be rather accurate (with the MAPE errors for WPP and SPP productions of about 5% and 3%, respectively, and MAPE for OHL ampacity being lower than 1%), highlighting the potential that ANNs could have for increasing the reliability of these forecasts. By pairing these with the Digital Twins, the additional options that would be at the disposal of the system operators if these became new standard were illustrated (inter alia, these were timely detections of contingencies and FSP selection).

On top of these analyses, an additional task that was completed by the partners in Bulgarian pilot was the development of the optimization algorithm dedicated to the selection of connection points of the set of production and storage units. The method picked for this was genetic algorithm and its usage was illustrated on the EHV-HV Digital Twin of Bulgarian system. In it, the optimization of points of connection for the three virtual wind power plants and one battery storage was simulated, with the minimization of the percentual loading in the selected part of the grid being used as the criterion for the optimization. The process itself only took several minutes and the results, being given in optimal connection points for each of the analysed units, were confirmed both by brute force and by running the optimization several times and getting the same results every time. The efficiency and reliability of these analyses confirmed that the optimization techniques could indeed be a great asset for system operators, especially when it comes to the tasks in which it is necessary to consider a large number of factors. The selection of connection points for the new units provides a great example for such a task.

The short duration of all performed calculations indicated that their practical application wouldn't cause any delays in the operative processes in the system operators and could, as such, be applied in everyday work. However, before that is even considered, it is also necessary to analyse the remaining aspects, other than the technical ones, which could be affected if this happens. That, along with some enrichments that will be implemented in the developed solutions (examination of the ANN potential for the demand forecasting, for instance) and evaluation if all of the tasks of the pilot were completed successfully, will be the topic that the Bulgarian partners will switch their focus to in the final year of TwinEU project. Of course, the final year will also be dedicated to discussing the potential to scale the developed solutions up to the level of EU, aligning them fully with the vision of united European grid.

1 Introduction

TwinEU enables new technologies to foster a cutting-edge concept of the Digital Twins (DTs) and their potential applications in the complex operation of the power systems, while, at the same time, determining the conditions for interoperability, data and model exchanges through standard interfaces and open application programming interfaces (hereinafter: APIs) to external actors. What is expected here is an advanced level of modelling that is, assisted by the artificial intelligence (AI) based tools, capable of exploiting the high-performance computing infrastructure in an adequate manner, thus getting an unprecedented ability to observe, test and, in its final state, simulate the pan-European energy infrastructure by using its digital replica. In order for this to happen in a way that will be both reliable and efficient, TwinEU needed to gather sufficient number of partners all over the European continent. In line with this, TwinEU involves quite a large number of partners, spanning across 15 European countries, fulfilling the first necessary precondition for its work to become successful.

Bulgaria is one of the fifteen countries that are represented within the TwinEU project, with the work of the partners involved in the Bulgarian pilot focussing on Tasks 7.4 and 7.5 within work package 7:

- **Task 7.4**: Optimal DER integration with advanced forecasting and capacity planning, focused on development and testing of the Digital Twins for the Bulgarian electricity grid. Digital twins include grid models, cross-border energy exchange models, and high-resolution RES production and OHL ampacity predictions (by utilizing the modern algorithms founded in the artificial neural networks (hereinafter: ANNs)) for power system state forecasts. All of these support frequency and voltage control in grid, congestion management, and DERs optimal valorisation for flexibility. More on DTs used as part of these activities can be found in the description given in Chapter 3.

- **Task 7.5**: Optimal DERs and storages location selection and connection point for grid planning, which also focuses on the development and testing of the defined DTs of the Bulgarian electricity grid. These DTs valorise grid models to study the optimal points of connection for the vRES and the batteries, taking into account both technical capabilities of the system and the geographical specificities that are relevant for work of the vRES. These same Digital Twins can also be used to evaluate potential grid upgrade needs to host the extensive capacity. Since DTs needed for both this task and Task 7.4 need to model Bulgarian power system in great detail, an effort was made to create a single set of Digital Twins that is both accurate and robust to accommodate both tasks.

Both of these tasks were set to start in the 9th month of the project's lifetime (September 2024) and will last up until the 33rd month of the TwinEU cycle (September 2026). In order to keep track of the actions taken by the partners in the pilot and to assess the progress made in the various stages of the solution's development, the final deliverable of Bulgarian pilot (D7.3) has an interim version in November 2025.

1.1 Partners in the Pilot

Activities foreseen for the Bulgarian pilot of TwinEU project were split among five partners, with each of them contributing to the defined tasks in line with their primary area of work and expertise, and combining their knowledge to achieve benefits expected from the project.

ESO EAD (ELEKTROENERGIEN SISTEMEN OPERATOR EAD), as the transmission system operator of Bulgaria. In line with that, their primary role in the scope of the pilot's work was focused on the parts which referred to the operation of the transmission grid and its technical characteristics, with the particular focus in the initial phases of the TwinEU project being on the verification of the EHV-HV Digital Twin, as described in the upcoming chapters.

EDG West (ELECTRODISTRIBUTION GRID WEST AD), as the operator of the western parts of the distribution grid in Bulgaria. According to this, their primary role in the work of the pilot was related to the operation of the distribution grid in Bulgaria, with the attention given to the distributed sources and the demand. They were also fully in charge of the verification of the MV Digital Twin, as described in the upcoming sections of this deliverable.

EE (ENTRA ENERGY), as the market party owning the wind plants and the hydro power plants in Bulgaria. As such, they provided completely different perspective to the pilot from one offered by the system operators. In accordance with it, their activities have dominantly been dedicated to checking the scenarios and the conclusions related to the behaviour of the market actors, as well as the alignment of the pilot's efforts with the valid legislation.

SETECHCO (commonly listed as: YUGOIZTOCHNOEVROPEYSKA TEHNOLOGICHNA KOMPANIA OOD), as provider of the advanced information tools and technologies. Since the envisaged scope of the work of the pilot revolved around utilization of cutting-edge technologies on the problems that are related to the power grids, the efforts of this partner have, for the most part, been focused on developing the necessary software codes and solutions.

SCBG (SOFTWARE COMPANY EOOD), as second provider of required services related to the information technologies. This partner has dedicated its work to bridging gap between modern technologies (the ANNs) and the practical needs of the project (such as the forecasts of the vRES productions, as well as the OHL ampacities based on climatic conditions), thus complementing work of all of the previously listed partners in the Bulgarian pilot.

1.2 Defined Timetable

As it was mentioned in the introductory section of this chapter, the work of the Bulgarian pilot was focused on two tasks assigned to the involved partners at the very start of the project's lifetime. Both tasks have been almost completed by the date of this deliverable's drafting. The detailed breakdown of foreseen activities and major checkpoints can, along with expected deadlines, be seen below (some of the deadlines shown here were dictated by the project's time-plan and the expectations regarding the availability of the material, whereas the others were set by partners based on their experience):

- **Month 6** (June 2024): complete definition of the Digital Twins and the finalization of the initial suggestions of Use Cases that can be used to illustrate the work of the Bulgarian pilot – at the time of the drafting of this deliverable, this step has been fully completed and verified;
- **Month 12** (December 2024): full description of the Use Cases and initial version of the template for data collection (has to be completed with the proper partners' coordination) prepared – at the time of the drafting of this report, this step has been completed and verified;
- **Month 16** (April 2025): template for the data collection distributed among the partners, with some of the data already prepared and verified; preliminary version of the D7.3 drafted – at the time of the drafting of this deliverable, this step has been fully completed and verified;
- **Month 18** (June 2025): input data collection completed; codes needed for the automatization of the processes described in the relevant Use Cases drafted and checked against the DTs – at the time of the drafting of this deliverable, this step has been fully completed and verified;
- **Month 23** (November 2025): codes fully written and verified; first set of the demonstrations completed, with results available; first full version of D7.3 of TwinEU project available – at the time of the drafting of this deliverable, this step has been fully completed and verified;
- **Month 30** (June 2026): additional demonstrations (if any additional demonstrations turn out to be necessary) done; obtained results evaluated; exploitation plans for the solutions made – at the time of the drafting of this deliverable, this step has yet to be initiated in months to come;
- **Month 33** (September 2026): final activities expected from the involved partners completed; final version of the D7.3, including the appropriate exploitation plans, written and published – at the time of the drafting of this deliverable, this step has yet to be initiated in months to come.

What is important to highlight here is that, at the moment of drafting of this report, the project has already reached the fifth out of the seven steps listed above, so it is already possible to estimate is there were any serious delays that could harm the timely completion of the activities. Even though there was admittedly some rescheduling (drafting of the codes took place sometime after June 2025), none of that harmed the big picture of the pilot, so everything is entirely back on track by this point.

1.3 Objectives of the Work

The work that has been done within the Bulgarian pilot has been split into two main tasks – Task 7.4 and Task 7.5. Hence, the objectives of the invested efforts needed to be fully aligned with the targets set before these tow tasks. As the main objectives of the Task 7.4, the optimal integration of the renewable energy sources has been broadly defined. It was intended for this goal to be achieved by applying the advanced forecasting and capacity planning methodologies (ANN-based forecasts of the production powers of the selected units and ampacities of the predefined set of lines). On the other (but still rather related) hand, Task 7.5 has been aiming at the selection of the optimal locations of the potential flexibility resources in the grid, with sources being either RES or storage systems. Since the main activities related to these tasks have been done successfully at the time of reporting in this document, it can be declared that both of these objectives were reached. The manner in which this was accomplished will be the topic of the upcoming chapters.

1.4 Outline of the Deliverable

Chapter 2 gives a brief overview of the methodological approach that has been adopted, focusing on the consequential order of the steps performed by the partners in the pilot in order to reach the mentioned targets.

Chapter 3 provides an insight into the DTs that have been developed in the scope of this pilot, giving a short description of the scope covered by each of them, the format in which they were created, and the purpose that they have in the pilot and the actions performed by it. In addition to that, its last subchapter also holds information on the ANNs as the AI method and the manner in which this technique has been utilized for the needs of the Bulgarian pilot. This subchapter is aimed at the readers that do not have previous experience with ANNs in order to enable them to understand the obtained results and presented conclusions on the advancements properly.

Chapter 4 describes the Use Cases utilized to the illustrate achievements made within the pilot, focusing both on BUCs (Business Use Cases – there were ten of those and one could find their outlines in the April 2025 version of the deliverable as well) and on SUCs (System Use Cases – there were four of those and this is the first time their features are in any deliverable, as they were envisaged after the completion of the preliminary version of the report).

Chapter 5 focusses on the Data Collection process, giving substance on both the templates distributed between the partners and the responses obtained from them, highlighting the fall-back options that had to be adopted in cases in which some of the information were either unavailable or, which also happened, held confidential and thus could not be used for the project's purposes.

In continuation of this, Chapter 6 showcases the results. It is, in order to establish the link with the previous parts of the document, divided into subchapters dedicated to one of the Use Cases each. This also gives context on how the collected data was used.

In the end, Chapter 7 acts as a resume of the achievements of the Bulgarian partners' work and as a list of the work that remains to be done within the pilot before the project concludes.

1.5 How to Read this Document

By reading the previous overview, one can see that this deliverable was envisaged as a stand-alone document, in a way that it provides all of the necessary information for the reader to properly follow the undertaken process and to critically evaluate the results given in the final couple of chapters. This can be done even without reading any external documents or the material regarding TwinEU project.

2 Methodological Approach

This chapter presents the methodological approach applied in the work.

2.1 Flow of the Process

The process comprises four parts. Figure 2-1 shows the first part of the process, covering the period from the start of the project to the moment in which the DTs were identified and data collection could be initiated.

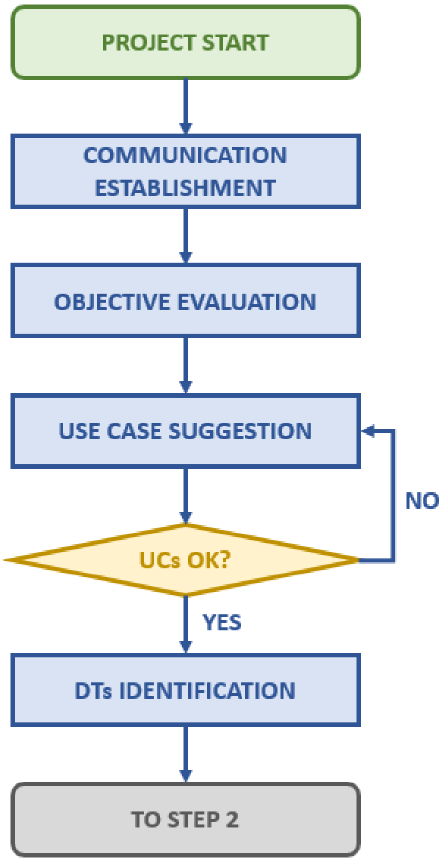


Figure 2-1 – Diagram of the process (Part I)

Once the project started and the communication between the partners was established, the first step was to carefully observe the objectives put before the Bulgarian pilot and to evaluate the steps which had to be taken in order to avoid any issues and hiccups that could stem from oversights made at the very beginning and inadequate planning of the available time and resources. It was thus vital to make at least the rough estimation of the duration of each step envisaged within the lifecycle of the project.

Once that provisional plan was made, it was necessary to propose the Use Cases that would later on be used to illustrate the accomplishments of pilot's work adequately. Here the most difficult challenge was to determine the needed number of the Use Cases, since they, as it was already mentioned, had to demonstrate the outcomes of the Bulgarian partners' work, but it was also essential to avoid them becoming repetitive, as that would just muddy the points which were desired to be made. After some revisions, the list of Use Cases with which all of the partners were satisfied was reached. That is the list that will be explained in the Chapter 4 of this deliverable. In turn, the completion of the list of Use Cases made it clear which Digital Twins needed to be developed for all desired results to be obtained. Once the DTs were selected, it was time to move on to the next part of process, shown in Figure 2-2.

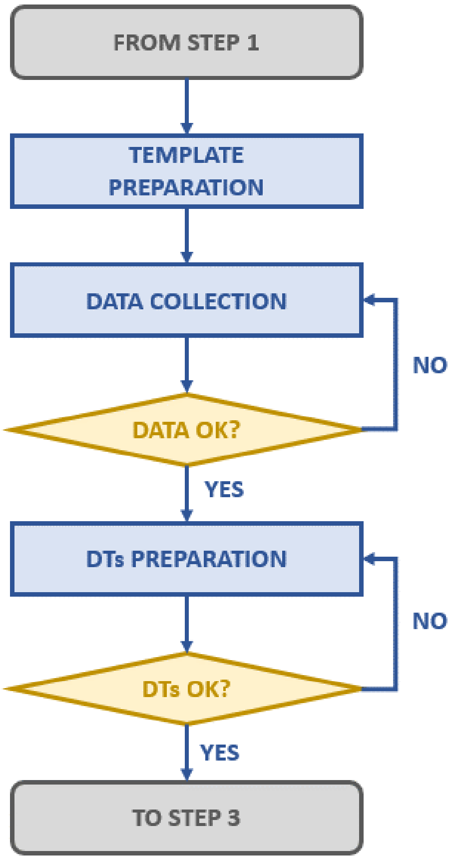


Figure 2-2 – Diagram of the process (Part II)

Once the DTs were known, it was also possible to identify which data will need to be collected and which partner will be able to provide which of the necessary inputs. As such, the duties were divided in a way that each of the partners covered the part that was close to their standard area of operation. Hence, ESO EAD provided the information that was related to the transmission system of Bulgaria and the facilities which are connected to it, whereas EDG West was in charge of delivering the information related to the distribution grid for which they are responsible. Entra Energy provided information from the point of view of the market participant that would otherwise be unavailable to the operators and the information technology providers as it does not fit either of their areas of expertise. Finally, the IT providers had their role in preparation of the templates for data collection before it took place and in verification of the delivered set of information once the initial phases of the collection were finished.

Once the datasets were fully prepared and verified, it was time to utilize them in order to develop the identified DTs, with this process taking place in two individual steps. The first one was the actual evaluation of the collected simulation models (the ones related to the grid were collected in the PSS/E software tool format, while the one related to the cross-border energy exchange had to be provided in the ANTARES tool software format, which will be reflected upon in Chapter 3). The latter step here included the work on the ANNs (training and testing part, forecasts were not done yet), as well as the codes that were necessary in order to evolve the regular simulation models into the desired DT shape.

Those codes were mostly dedicated to the automatization of the necessary analyses and the export of the obtained results in the specified form. With this out of the way, the entire process could move on to the next step, illustrated in the Figure 2-3 in the same way as the two steps which preceded it.

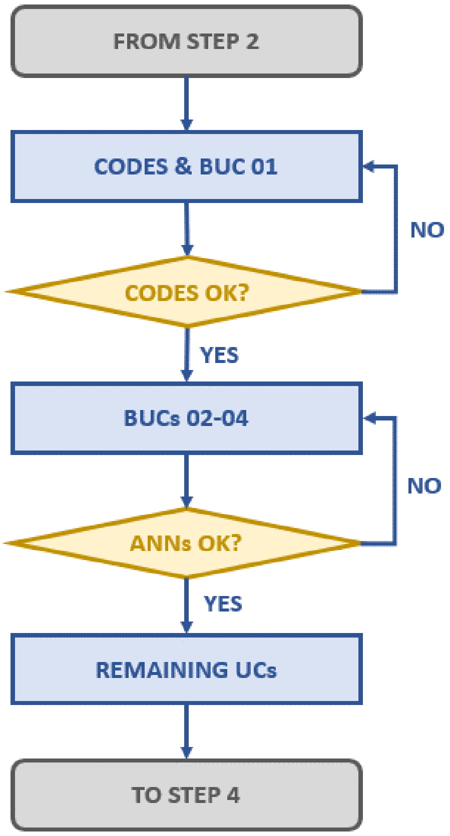


Figure 2-3 – Diagram of the process (Part III)

The continuation of the programming process initiated in the previous step took place here, in the form of the coding of automated reliable data exchanges among the different DTs that were created beforehand. This primarily targeted the need to import the results of the ran ANN-based forecasts to the grid-founded and market-founded DTs in order to perform the activities enveloped within the defined Use Cases later. For this to happen, the programming was done in three different languages, selected in such a way to be compatible with the formats used. Hence, Python programming language was utilized for anything related to PSS/E, whereas R language was used when the data exchange had to be done with the ANTARES software tool. These codes represented the essential part of the BUC 01 of the pilot as well and will, as such, be mentioned both in the general description of this BUC and in the part of this deliverable that will be concentrated on showing the outcomes of UCs in the pilot.

After that, the forecasts could actually be performed by using the ANNs that have been developed and tested before, which also marked the completion of the BUCs 02, 03, and 04 of the Bulgarian pilot, with BUC 05 also following shortly after. Once that part was completed, the fully automated models with the coded way of importing the performed forecasts into them became available to the partners, which also meant that the direct precondition for remaining BUCs and all SUCs has been fulfilled and that the activities on those could start as well. The order in which those were completed doesn't quite correspond to their numbers, as the BUC 06 was the last one to be finalized. However, this has to do with the nature of this BUC and the fact that it differs significantly in scope and goal from the rest of the Use Cases (this was the Use Case related mostly to Task 7.5, while the rest of them primarily aimed at the goals of Task 7.4). At last, all of these were successfully completed, making it possible to close this part of the process and move to the final part, illustrated in the diagram provided in Figure 2-4.

Figure 2-4 – Diagram of the process (Part IV)

This part is scheduled to happen in the final year of the project cycle and to focus mostly on the ways in which the outcomes of all of the previous steps can be exploited and utilized later, once the project is completed. Success of this step depends entirely on the previous steps, as there is no discussion on the solution's practical implementation if there is no announced solution in the first place. Nevertheless, as the solutions that were expected to be developed have actually been properly tested and verified, it can be confirmed that this precondition was fulfilled and that the fourth and final step can take place just as expected.

2.2 Synergy with Other WPs

To understand the upcoming parts of this report, it is needed to highlight some of the information that was forwarded by the Bulgarian partners to other WPs and some of the assessments that were performed by Bulgarian partners, but included in deliverables of other WPs. It should also be highlighted that the activities mentioned here will not be mentioned or expanded upon in the future chapters in order to avoid any kind of undesired repetition both between this deliverable and deliverables of the other WPs and between this chapter and the chapters that will come after it.

The primary goal here was not to point out any action performed by the Bulgarian partners that was mainly a part of the other WPs' scope, but to give the reader a bit of the background regarding the position of pilot within TwinEU project and to answer some of the questions that would otherwise remain unresolved by the end of the deliverable. Hence, no descriptions of, for example, the ways in which the Bulgarian partners participated in the public promotion of the TwinEU project shall be given, although this was primarily the task of WP 10, simply because the knowledge of this would not make it easier for reader to understand the accomplishments of the pilot and the results of the partners' work. By applying this criterion, it was determined that the attention in this subchapter should be paid to two major actions.

The first such action was the definition of the three layers by which the architecture of the pilot and the UCs involved in it was defined, performed as part of the Task 3.3 in WP3. This was deemed vital as it could enhance the comprehensiveness of the outcomes presented later on by giving an insight into the envisaged system behind those results. Those three layers were:

- the component layer (in which the components involved in the UCs were defined, along with the physical ways in which the connection between them was achieved – here the component layer, rather than describing actual physical components, gave insight into the configuration of the system envisaged within the simulation environment in which all of the work was done);
- the communication layer (similar to the component layer, but with standard communication protocols added to the physical manner of connecting – once again, the information provided in this layer referred to the expected manners of communication that could be achieved if this solution was practically utilized and not to the actual communication that happened), and
- the information layer (in it, exact information that gets exchanged between the components and the data models had to be defined – same as for the previous two layers, the information was not actually exchanged, but exchange was simulated in the appropriate environment).

As an example of these layers and the format that was used, the information layer sent to the WP3 is enclosed in Figure 2-5. For more details on this diagram and the goal of each of its sections, one could look into deliverables of WP3 as well, just to be able to get a complete picture. The other two diagrams (related to the other two layers) appear quite similar to this one, with the differences being not in the basic configuration of the solution, but rather in the main goal that was set before each of these layer

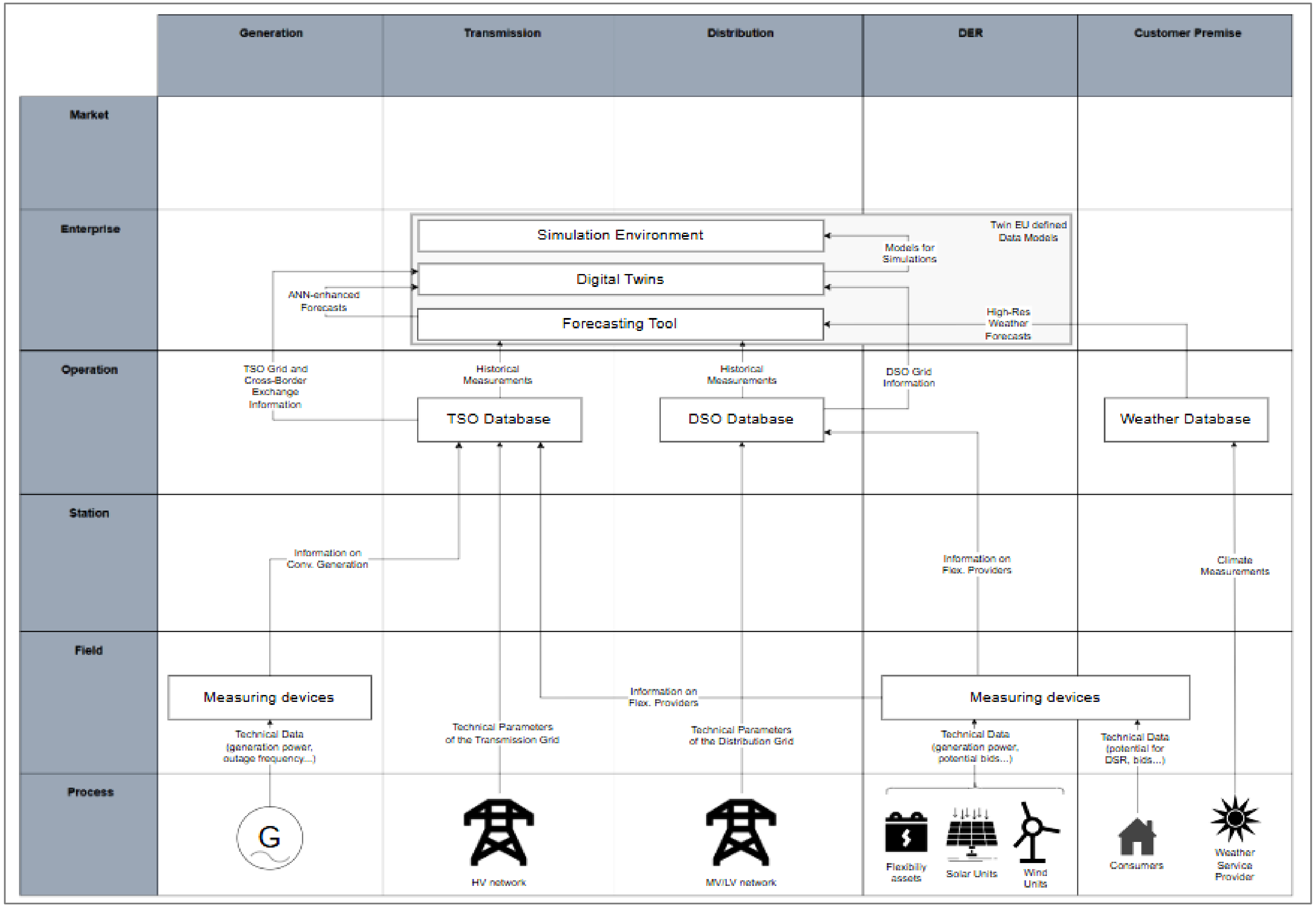


Figure 2-5 – Information layer of the Bulgarian pilot architecture

This diagram shows which exact components participate in the Bulgarian pilot UCs, where each of them would be located (in the TSO or DSO, at customers' premises, etc.) and what kind of data would need to be delivered by whom and to whom in order for the processes defined here to succeed. For instance, it is clear that the technical parameters of the transmission grid would need to be stored in the TSO database after getting collected in the field. This is why there is an arrow between the HV network and the TSO database in the diagram. The same can be stated for the DSO database and technical parameters of the MV and LV grid. This diagram (and the diagram of other two layers) could prove to be essential in case the practical implementation of the solution developed in the Bulgarian pilot moves beyond the scope of TwinEU project, justifying decision to include it in this report as well.

A national regulatory analysis has been conducted by the Bulgarian partners for the work of WP9 with the goal of checking whether the currently valid regulatory frameworks in the countries active in the TwinEU project support the goals of the project and the implementation of the solutions created by the parties in it, or could there be some misalignment between the regulations in force and the proposals made within the project. As the part of this activity, the Bulgarian partners were asked to pick those regulations, action plans, and strategic documents of Bulgaria that are relevant to the scope of the project and to estimate if those are in line with what is suggested through the Bulgarian pilot. The final selection of acts is given here:

- Energy Law;
- Energy from Renewable Sources Act;
- Final Updated National Energy and Climate Plan 2021–2030;
- Annual Report to the European Commission;
- Ten-Year Development Plan of Bulgaria's Electricity Transmission Grid (2025–2034).

For all of these, short descriptions were provided, together with the elaboration of their relevance for the key area under analysis, of their relevance for the TwinEU project and its outcomes, and of the barriers and potential issues related to those acts. For instance, for the Annual Report to the European Commission, the relevance for the TwinEU project was explained by this document providing accurate regulatory snapshot on how RES integration, balancing, and market transparency are evolving in the country, by demonstrating the real-world uptake of DERs and flexibility challenges, which are central to the DT modelling, and by identifying the possibilities for pilots in the cross-border market coupling, consumer data use, and flexibility services. Regarding the barriers related to this document, there was a need to emphasize limited smart metering deployment that restricts data granularity for prosumers and flexibility, market immaturity for flexibility services (DERs and storage have limited participation), grid constraints and high investments needed in order to mitigate congestions, regulatory instability and frequent adjustments to the support schemes which are reducing investor certainty, and issues regarding the cybersecurity and interoperability gaps in the digital market infrastructure. Contribution also includes the recommendations regarding each act, which, for the same Annual Report, were that there's a need to continue network expansion and modernization, to strengthen market monitoring, to develop deeper regional integration through the interconnectors and the harmonized cross-border capacity allocation, and to support further market liberalization. This kind of assessment, included in more detail in deliverables of WP9, could give the reader a better idea of the environment in which the solutions described here were developed and to which extent these solutions are aligned with the regulatory framework. With this, the general introductory part of this deliverable can be considered finalized, with the next chapters moving on to describing the specific parts of the developed solutions.

3 Digital Twins in Bulgarian Pilot

By observing the complexity of the work included in Task 7.4 and Task 7.5 of the TwinEU project, one could easily understand why the challenges that have been set ahead of the Bulgarian partners were not to be underestimated and why it was necessary to plan out the adequate set of Digital Twins properly. In accordance with this conclusion, it was decided by the partners to focus on the four major DTs and several smaller DTs as well. Main characteristics of these DTs can be found in the list below.

3.1 EHV-HV Digital Twin

The first Digital Twin needed for works of the Bulgarian pilot was the EHV-HV (extra high voltage and high voltage) model of the transmission system of Bulgaria. Creation of this DT was done in tight collaboration between the IT providers and the TSO in order to ensure that all of the information used is up-to-date. Therefore, it was based on the existing models of the grid, used by the TSO itself. Format in which this model has been delivered is one compatible with the PSS/E software tool. Improvement achieved in this DT compared to the regular model was the high level of automatization and pairing with the forecasts done by the ANNs, achieved by drafting the custom-tailored codes in Python. Main interface in which the majority of work is done in PSS/E software environment is shown in Figure 3-1.

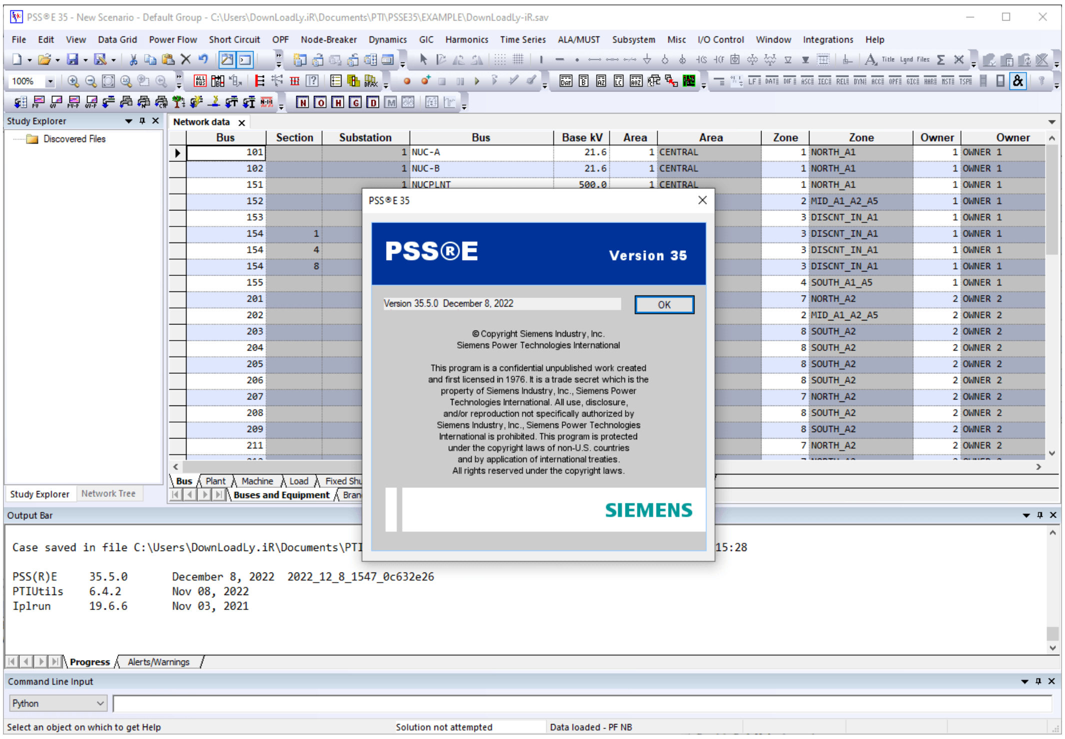


Figure 3-1 – PSS/E (version 35) software environment

The screen above does not represent the exact nodes or their identifiers in the model of Bulgaria, but rather uses one of the generic test-grids coming with the software installation. This is sufficient to conclude that the software is mostly based on the tabular forms and properly inputting information into it. Of course, there is a possibility to show relevant parts of the grid on custom-made single line diagrams, but the largest part of the work is done in the form shown above. PSS/E tool is also used in most of the TSOs in Europe, improving the scalability of the solutions developed in the Bulgarian pilot.

In addition to this, it needs to be mentioned how exactly is this Digital Twin advanced than common grid model that is used by the Bulgarian TSO in everyday practice. Well, first of all, it is equipped with the made-for-purpose scripts written in Python (as it is the language that is compatible with the PSS/E software tool) which serve for the automatic implementation of the forecasted values and the results obtained from the cross-border energy market Digital Twin (that will be discussed a bit later on). The forecasts were performed by appropriate ANN-trained DTs which are also going to be described later. Moreover, this DT is, via the forecasting ANNs, paired to certain extent with the climate parameters relevant for the grid operation, guaranteeing the precise incorporation of the forecasts of the chosen set of the relevant technical parameters into the grid model and adequate estimation of their impacts.

3.2 MV Digital Twin

Second Digital Twin needed for completion of the activities of the Bulgarian pilot was MV model of the part of distribution system in Bulgaria. It is considered partial as it doesn't consider the complete MV grid in Bulgaria, but only the parts of it that were of interest for the project and Use Cases defined in it. These parts were located in regions with the high potential for integration of variable renewable energy sources, such as wind and solar power plants. This choice allowed the partners to fully estimate the effect of the improved generation forecasts on the operation of the system, in line with one of the main targets of the Bulgarian pilot. It was based on the data that was delivered by EDG West partners through the data collection process. To be compatible with the EHV-HV DT, it was also created in PSS/E tool. Of course, this model once again had to be enhanced by codes in Python programming language and ANN-trained Digital Twins for the forecasts of the parameters relevant for this part of the grid.

By using the same software tool and programming language once again, compatibility between the EHV-HV DT and MV DT was achieved. This kind of compatibility was particularly important as both of these were applied together in some Use Cases. This was necessary in order to properly evaluate the impact that the different system subjects (production, storage, demand) connected to distribution grid can have on the work of the transmission system. In line with that, effects of improved forecast accuracy had to be determined while taking both of those into account, leading to the decision to use the same tools for model building (along with the automatization codes). Surely enough, this DT had to pass the thorough check done by the Bulgarian DSO before its utilization for any analyses. Regarding the analyses themselves, it should be clarified that these two Digital Twins (individually or combined) were used for load-flow calculation, N-1 security assessment, and maintenance scheduling checks, but could be also used, for example, for the calculations of active losses or the voltage state estimations.

3.3 Cross-border Energy Exchange Digital Twin

Third Digital Twin that was made during the work of the Bulgarian pilot partners was the model of the energy market, focusing mostly on the cross-border energy exchange between Bulgaria and other countries in the same region – cross-zonal exchanges mostly. Creation of this model allowed partners to estimate the impact that updated data on generation behaviour, made by combining the improved RES forecasts and data regarding the other existing units in the Bulgarian grid, can have on parameters such as cost of the system operation and values of power delivery reliability indicators. Furthermore, the results obtained by using this model were the basis for the creation of the EHV-HV and MV Digital Twins, described in the previous two sections. This DT has also been based on the existing models of the cross-border energy market, in the format currently used for this purpose – the ANTARES package.

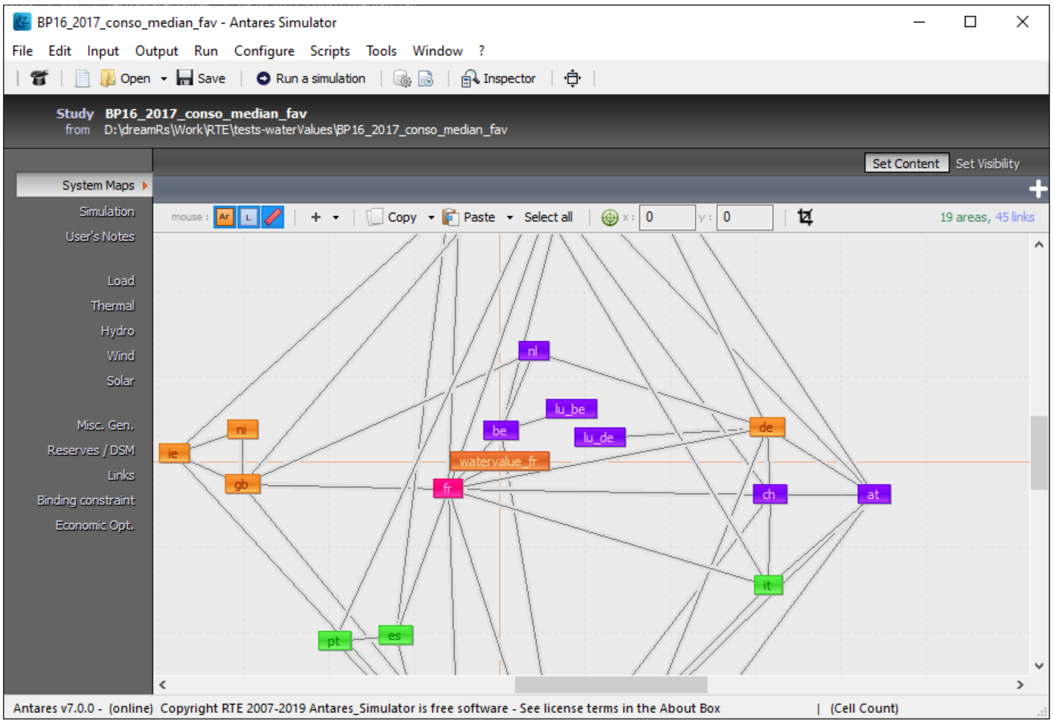


Figure 3-2 – ANTARES software environment

For the selection of the tool, thorough discussion between the Bulgarian TSO and IT providers had to take place. As the priorities related to the selection process itself, it was decided that the tool had to be robust and intuitive enough to adapt to the different needs that might come to occur during the project's lifetime, but also provide the results detailed enough to feed the previously mentioned two DTs. Additional plus would be familiarity of the engineers in the TSO with the tool and its capabilities. With the help of the ESO EAD partners, ANTARES software tool was singled out. As the automatization of some parts of analyses was also needed (which also represented the main difference between this DT and the regular ANTARES model, along with pairing it with ANN-done forecasts), it was determined that the codes needed to be written in R programming language, recommended by the fact that it has an entire library dedicated to communication with the ANTARES tool and the results coming from it.

3.4 High-level Digital Twin

Before anything else, it should be underlined that this is the only DT out of all described here that is yet to be developed in the final year of the project. This is not an issue regarding the timetable of the project, as this is also the only DT that wasn't needed for analyses or Use Cases listed within the pilot due to its nature. Namely, this DT will be developed for high level analysis performed by governmental bodies, institutes, regulatory authorities and universities. It's worth noting that the focus here will primarily be on university and potential academic usages, especially when it comes to writing scholar papers and conducting research on the innovative proposals. This DT will be developed to illustrate the coordination between different parts of the energy system, such as transmission grid, distribution grid and cross-border electricity market. As it will include less details compared to previous DTs, it will be easier and faster to use and to extract results from. This DT will be only used for rough estimations, not for the detailed assessments. Hence, efficiency of doing calculations and providing results is the priority for the development of this DT which, once finalized, will enable the overview of entire grid.

3.5 ANN-trained Digital Twins

In order to properly understand what was done by applying the ANNs and how they were adapted and trained for the pilot's goals, one must first have a basic knowledge of ANN as the technique. For that to be ensured, the first part of this subchapter will be dedicated to providing a brief overview of that knowledge. Therefore, in the beginning it should be emphasized that machine learning represents a discipline that enables the computers to learn without being explicitly programmed. It is a subfield of artificial intelligence, derived from the research in the areas of pattern recognition, computational learning theory, and utilizing the statistics to develop algorithms that learn from previously available data. In addition to combining statistics, optimization, and linear algebra, machine learning also relies on the graph theory, functional analysis, and other areas of mathematics. Machine learning algorithms typically fall into one of two main categories: the supervised learning and the unsupervised learning.

Artificial Neural Networks (ANNs) are example of supervised learning. ANNs are a powerful tool in modern machine learning, offering the ability to learn patterns and dependencies from data. In the context of power grids' Digital Twins, ANNs are used to model complex, nonlinear behaviour of system components such as wind turbines, solar modules, and OHLs. ANNs represent the new generation of information processing systems that are capable of learning and generalizing from training data. These networks are composed of a large number of densely interconnected processing elements, also known as neurons, which are structured in regular architectures. The idea behind the development of neural networks was inspired by the desire to somehow model the behaviour of neurons in the human brain.

In this context, the focus is on their application to solve the supervised learning problems, where a dataset with known inputs *x* and corresponding output values *y* is used to train the network. During training, weights of all neurons – where the network's "knowledge" is stored – are adjusted to capture relationship between inputs and outputs. Once trained, neural network can predict outputs for new inputs where the corresponding outputs are not known in advance. Basic concept of artificial neural network, proposed as a simple mathematical model of a biological neuron, can be seen in Figure 3-3. The meaning of the synapses, neuron cells and activation functions (mentioned in the diagram shown in the figure below) will be explained later on, in the descriptions referring to the ANN work as a whole.

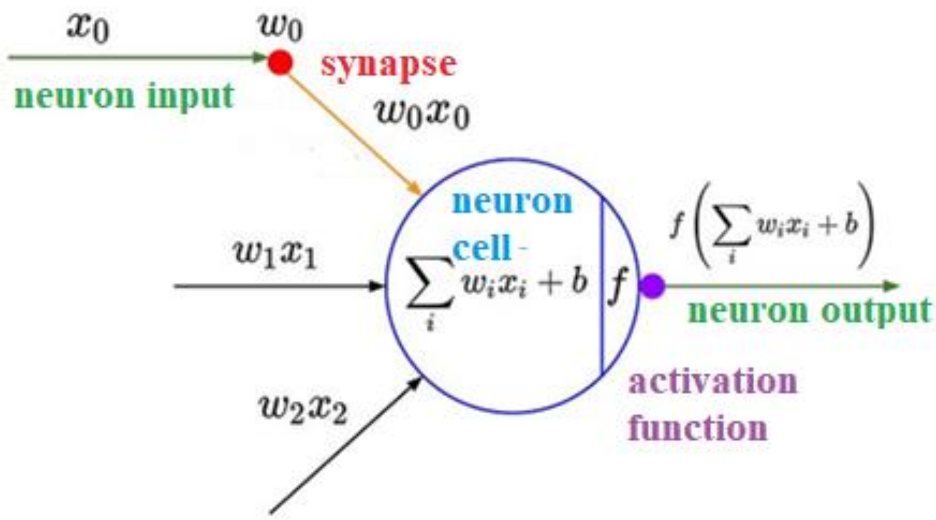


Figure 3-3 – Mathematical model of a biological neuron

The mathematical model of a biological neuron aims to emulate the fundamental behaviour of real neurons in the human brain. In this model, a neuron receives multiple input signals, each associated with a specific weight that determines the strength of connection (analogous to synapses that can be encountered in the biological neurons). These weighted inputs are then combined into the single value through a linear transformation, typically represented as shown in the Formula (3.1), provided below.

$$net = \sum_{i=0}^{n-1} w_i x_i + b \tag{3.1}$$

In the Formula (3.1), w_i are the weights – the variable parameters related to the input components, whereas *b* is a variable parameter representing a free term, and *x* represents the input of the neuron. Some of the other possibilities for the transfer function are quadratic, polynomial, and spherical. Next, the result of this transfer function goes through activation function (in the form of $y=f(net)$) to obtain the final outputs of the neuron. Some of the most popular activation functions currently are: linear, sigmoid, hyperbolic tangent, ReLU, and Leaky ReLU. Linear function can be seen in the Formula (3.2).

$$f(net) = net \tag{3.2}$$

As can be concluded, this function is as simple as it can get, as it does not introduce any additional variables or constants. Sigmoid function, as a bit more complex one, can be seen in the Formula (3.3).

$$f(net) = \frac{1}{1 + e^{-net}} \tag{3.3}$$

The level of complexity of the function given in Formula (3.3) is definitely higher than direct linear relation. Next commonly used function is the hyperbolic tangent that is provided in the Formula (3.4).

$$f(net) = tanh\ (net) \tag{3.4}$$

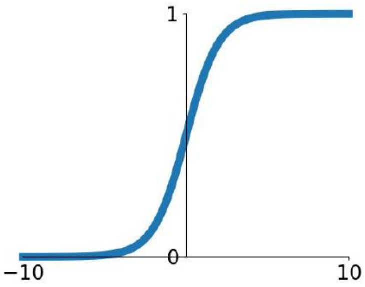
The previous formula is based on the continual geometric function. The following one, on the other hand, makes a turn in the behaviour based on whether the *net* parameter is greater than zero or not. This is Rectified Linear Unit function (or, as it is often abbreviated, ReLU), shown in the Formula (3.5).

$$f(net) = max(0, net) \tag{3.5}$$

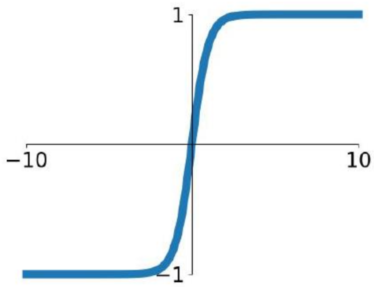
Final function that will have some dedicated space here is the one that also behaves differently if the *net* value is higher than zero and if it is lower than zero. However, in cases in which *net* is below zero, this function does not take zero value. This is Leaky ReLU function, illustrated by Formula (3.6).

$$f(net) = max\ (0.01 \cdot net, net) \tag{3.6}$$

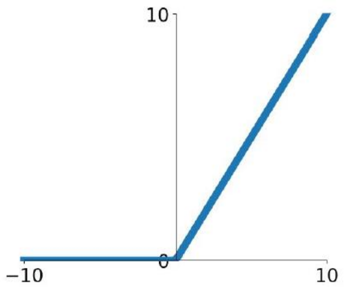
In Figure 3-4, the shapes of all of these functions can be seen, except the linear one. Namely, it was deemed not necessary to explicitly show the shape of this function, as it would only be one diagonal line going through the zero point of the diagram. By utilizing one of these functions, a single artificial neuron has been defined, marking the first step in the forming of the entire artificial neural network.



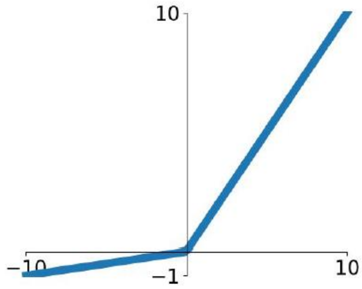
a) Sigmoid function



b) Hyperbolic tangent (tanh)



c) ReLU



d) Leaky ReLU

Figure 3-4 – Graphical representation of the activation functions

Now, it is time to explain how exactly a neural network can be made out of the single neurons that are explained on the previous page. For that, a feedforward neural network will be used. One layer of neurons here represents a set of multiple neurons with the same input. Each neuron then applies its own weight parameters to that input. Feedforward neural network consists of an input layer, hidden layers, and an output layer. The input layer receives the data that is fed to the neural network. Further, the hidden layers have as input the outputs of the neurons from the previous layer, and their output is used as input to the next layer. The output layer is the last layer in the network that should form a prediction based on the data fed to the input. The organization of ANN is demonstrated in Figure 3-5.

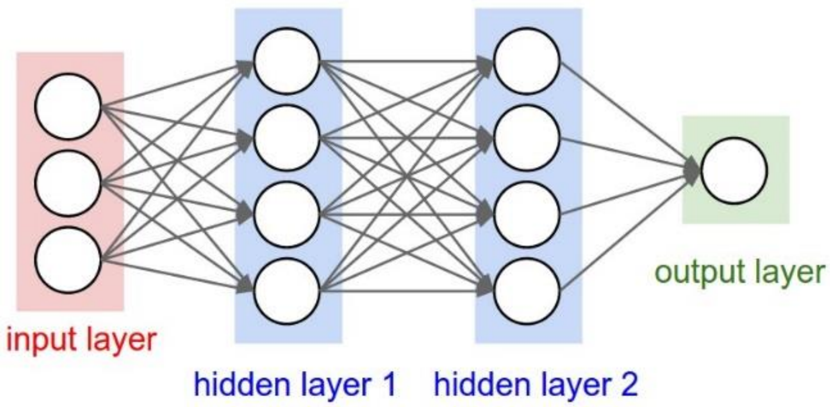


Figure 3-5 – Internal structure of ANN

In the case of solving a regression problem, such as prediction of a real value, a linear activation is usually applied to the output neuron. In the case of the binary classification, an output neuron with a sigmoid activation can be used, where the output value will simulate the probability that the neuron belongs to the first class, while the probability of belonging to zero class is calculated by subtracting the output value from unity. In the case of the multiclass classification, there is a generalization of the sigmoid neuron, by forming *k* neurons with linear activation in the output layer, where *k* is the number of different classes. After that, a soft-max function is applied over all the neurons in order to transform outputs into numbers that simulate probabilities of belonging to each class, as given in Formula (3.7).

$$\hat{p}_m = P\left(Y = m \middle| X = x^{(i)}\right) = \frac{e^{net_k{}^{(i)}}}{\sum_{j=1}^{k} e^{net_j{}^{(i)}}} \quad (3.7)$$

A neural network stores its “knowledge” in weights *W*, and therefore it is necessary to find a good set of weight parameter values for the problem that’s being solved. *W* is the set of weight factors that is adjusted while using the ANN. This is done by assuming a loss function *L(W*). When the loss function has a large value, it means that the network has poor performance on observed data set, while a small value of the loss function indicates the good performance. The goal is thus to find set of parameters *W* for which the loss function *L(W)* is the smallest. For the regression problem, linear output layer and the mean square error criterion are utilized. This is illustrated by the group of Formulae (3.8) - (3.10).

$$L(W) = \frac{1}{N}\sum_{i=1}^{N} L_i(f\left(x^{(i)}, W\right), y^{(i)}) \quad (3.8)$$

$$L_i = \left(\hat{y}^{(i)} - y^{(i)}\right)^2 \quad (3.9)$$

$$\hat{y}^{(i)} = net^{(i)} = f(x^{(i)}, W) \quad (3.10)$$

Formula (3.8) here represents the general form of the loss function. It can be seen that each data ($x^{(i)}$, $y^{(i)}$) from a set over which the loss function is calculated contributes. In this case, it contributes by calculating the mean square error between network output $\hat{y}^{(i)}$ and the actual output value $y^{(i)}$. The larger the mean square error, the greater the loss function and the worse the performance value on the observed data set. For regression, the criterion of absolute error is sometimes used, or the square of the error when the error itself is lower than some predefined threshold and the absolute value of the error when the error is greater than the same threshold (hence that large errors, which are above the threshold, do not increase their effect by squaring and force the network to focus the learning on that data). These two loss functions are illustrated by the following two Formulae, (3.11) and (3.12).

$$L_i = \left|\hat{y}^{(i)} - y^{(i)}\right| \quad (3.11)$$

$$L_i = \begin{cases} \left(\hat{y}^{(i)} - y^{(i)}\right)^2 & when \quad \left|\hat{y}^{(i)} - y^{(i)}\right| \leq a \\ \left|\hat{y}^{(i)} - y^{(i)}\right| & when \quad \left|\hat{y}^{(i)} - y^{(i)}\right| > a \end{cases} \quad (3.12)$$

In the case of solving the classification problems, the soft-max output layer is used in combination with a cross-entropy criterion function. This is shown in Formula (3.13), at the start of the next page.

$$L_i = -log\left(P\left(Y = y^{(i)} \middle| X = x^{(i)}\right)\right) = -log\left(\frac{e^{net_{y^{(i)}}{}^{(i)}}}{\sum_{j=1}^{m} e^{net_j{}^{(i)}}}\right) \quad (3.13)$$

The previous procedure has formed a neural network, as well as a loss function *L(W).* The next step here is to find a set of parameters *W* which minimizes the loss function. This is achieved by applying the gradient descent algorithm. The basic principle of this algorithm can be seen in the Formula (3.14).

$$W^{i+1} = W^{i} - \alpha \nabla L(W) \tag{3.14}$$

This algorithm operates by first finding the partial derivative of the loss function for every variable parameter $\frac{\partial L(W)}{\partial w_{ij}}$ and, based on them, gradient $\nabla L(W)$ is formed. This gradient has direction, with the direction of the steepest increase of the loss function in the parameter plane *W* getting monitored. As the loss function is minimized, a negative gradient (the opposite direction) is adopted. The iterations are repeated until some criterion is met: maximum number of iterations, minimum threshold of the loss function reached, or too small changes in the parameters seen in several consecutive iterations.

This procedure is generally very computationally demanding when dealing with a large number of parameters, as approximating the gradient requires evaluating the network output *p + 1* times, where *p* is the number of the network parameters. In feedforward neural networks, the exact gradient can be computed efficiently using a forward pass (to calculate the output based on the input) followed by a backward pass, during which all partial derivatives are computed using analytical expressions. This process is known as the backpropagation algorithm, and it was a key factor in the resurgence of neural networks in the 1980s. However, their popularity declined soon after, mostly due to limited availability of the data and the lack of computational power at the time. Today, the backpropagation algorithm is implemented in all major programming libraries that are commonly used for building neural networks.

Before applying this algorithm, the neural network's weights *W* must be initialized. This is typically accomplished by assigning random values drawn from a specific distribution – commonly Gaussian or uniform – to the parameters of each of the neurons in every layer. The parameters of the distribution are usually chosen based on the number of inputs and outputs for respective layer. These initialization procedures are also incorporated into modern neural network libraries. The common and undesirable effect that can sometimes happen when training neural networks is overfitting. This happens when a model performs exceptionally well on the training dataset but poorly on the unseen data. Overfitting arises because the neural networks are highly nonlinear and possess strong expressive power; if they are not properly controlled, they will learn every detail in the training data – including noise and faulty measurements. One standard technique that is applied to mitigate overfitting is regularization, which involves modifying the loss function. This modification is illustrated just below, in the Formula (3.15).

$$L(W) = \frac{1}{N}\sum_{i=1}^{N} L_i(f(x_i,\ W),\ y_i) +\ \lambda R(W) \tag{3.15}$$

Here the second term of the sum represents what is known as the regularization term. Commonly used type of regularization term uses the sum over all the variable parameters of the neural network, as can be concluded from the Formula (3.16), presented at the very beginning of the following page.

$$R(W) =\ \sum W^2 \tag{3.16}$$

As illustrated in Figure 3-6, first term of the loss function aims to describe the data in the training set as well as possible (blue line). Here it should be stated that it is not necessary to capture all details, since measurement noise and poor measurements are also present. The second, regularization term, forces the network to detect as simple a relationship between the outputs and the inputs as possible (green line). With the proper selection of the parameter *λ,* which determines the contribution of the regularization term to the original loss function, a desirable balance between the two effects can be achieved. With this process, the overfitting and all of the potential consequences of it may be avoided.

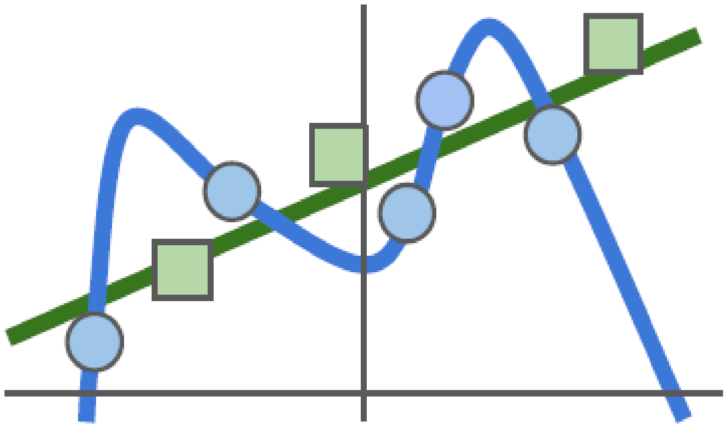


Figure 3-6 – Original loss function vs. the regularization term

At the beginning of any neural network application – or, broadly, any machine learning task – it is standard practice to partition the available dataset in two subsets: a training set and a testing set. The testing set is put aside and not used during the training or model development process. Only after the final model is trained does the testing set get used to obtain somewhat realistic estimate of model's generalization performance. Typically, 20% to 30% of the total dataset gets reserved for testing. The exact proportion depends on total amount of data available. If the dataset is small, reserving a large portion for testing may leave too little data for effective training. The testing set serves an important role: it helps to detect overfitting. When enough data is available, it is the common practice to further split training set into two parts: a training subset and a validation subset. A widely used rule of thumb is the 60-20-20 split: 60% of the total data is used for training, 20% for validation, and 20% for testing. Nevertheless, these proportions are not fixed and may be adapted based on the specific dataset and problem. While the testing set is used only once at the end of model development, the validation set plays a key role during the training phase, particularly for hyperparameter tuning. Just as the model's parameters (e.g., weights *W*) are learnt from training data, its hyperparameters – such as the network architecture, activation functions, regularization strength, and optimal number of training epochs – are chosen based on validation data. It is crucial not to use the testing set for hyperparameter tuning, as this would lead to data leakage and an optimistic bias in the performance estimate. Instead of this, choosing hyperparameters is done via the cross-validation. There, model is trained by using various combinations of hyperparameters on training data, and their performance is evaluated on validation set. The combination that yields the best performance on the validation set is then chosen as optimal.

The accuracy of the ANN can be evaluated through the values of the calculated errors. Some of the typical errors that are utilized to check the precision are MAPE (Mean Average Percentage Error), MAE (Mean Absolute Error), MSE (Mean Square Error), and RMSE (Root Mean Square Error). MSE measures an error in statistical models by using the average squared difference between observed and predicted values. RMSE measures the average difference between a statistical model's predicted values and the actual values. For the regression tasks, a common metric is MSE. For classification tasks, it may be the classification accuracy (percentage of the correctly classified instances), or an alternative metrics that account for class imbalance, such as precision or recall. However, for an estimation of the accuracy of the forecasts done in the scope of this pilot, MAPE value will be used, as shown in the Formula (3.17).

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\frac{|y - y_i|}{y} \cdot 100\% \tag{3.17}$$

Based on the large volume of input data and the transfer of information between artificial neurons, the created ANN can predict various output values, depending on the need of the user (that is, in this case, the system operator). Parameters that can be predicted in the scope of this pilot include, as was clarified before, the ampacity of the selected set of OHLs, and the power outputs of the wind farm or the solar power plant. Figure 3-7 now illustrates the mathematical representation of a neuron within an ANN trained for forecasting one of the desired parameters, which is the OHL ampacity in this case. More on the training and testing of these ANNs can be found in the Subchapter 5.4 of this deliverable.

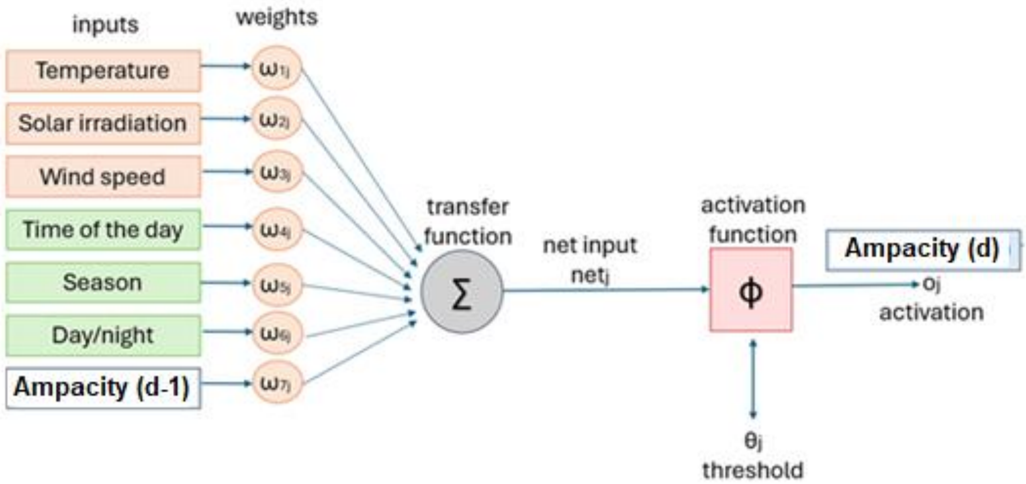


Figure 3-7 – Mathematical model of the ampacity-forecasting ANN

These ANNs that were dedicated to the forecasting subtasks have been treated as auxiliary DTs in the scope of the pilot. The term “auxiliary DT” here actually stands for the DT dedicated to simulating the behaviour of a single element or a small group of elements in the grid. Those DTs were developed for:

- wind turbines,
- solar modules,
- wind parks,
- solar parks, and
- OHL ampacities.

The ANN-trained Digital Twins were utilized in order to enrich and enhance the main EHV-HV grid, MV grid and cross-border energy exchange Digital Twins for all necessary grid operations and planning simulations, based on the existing network models and market information on Bulgarian system (as it was described in more details in the previous subchapters of this chapter). However, a question may be raised here that could require some additional attention. Namely, if somebody observes the list of the ANN-trained DTs, they could spot the curiosity that the third DT simulates a wind farm, whereas the first of them simulates a single wind turbine. In continuation of that, they could wonder why this was necessary and why it wasn’t possible to simply simulate the work of the wind farm by aggregating the characteristics of individual wind turbines in it. The response to this can be found in the fact that, in order to simulate the work of the wind farm, one would not only need to observe the work of each turbine in it, but also consider the way in which the turbines affect one another. The obvious example that proves this point can be found in wake effect, as given in the simplified illustration in Figure 3-8.

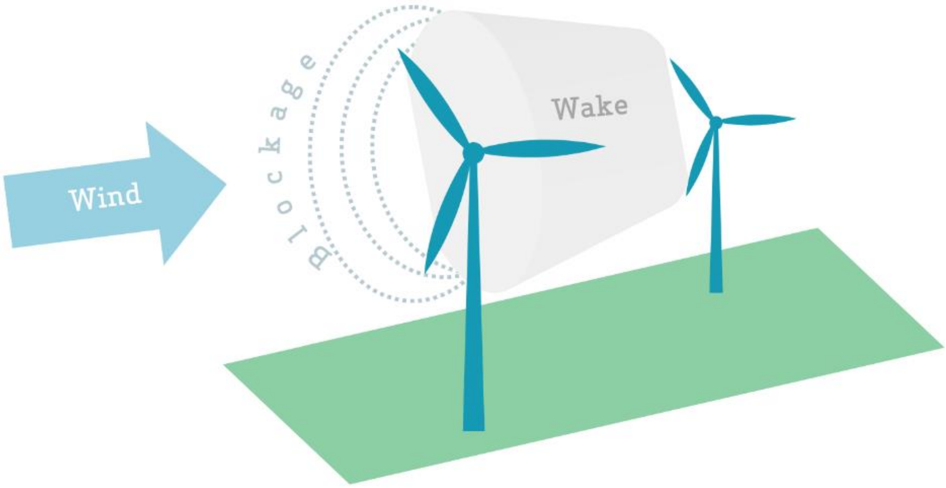


Figure 3-8 – Illustration of the wake effect in wind farms

This effect not only reduces the speed of the wind that reaches the "downwind" turbine, but it also increases the turbulence of the air that rotates its blades, thus reducing its efficiency by the substantial percentage. This is why it was not enough to simulate one wind turbine and then multiply its produced energy by the number of turbines in the observed wind farm. Therefore, it was necessary to also have a separate ANN-trained DT for the wind farm as a whole in order to make sure that the forecasts which need to be performed actually get done in a most reliable fashion and on a DT that indeed corresponds to the situation present in real-life. Similar statement can be made for the solar modules (second listed auxiliary DT) and the solar parks (fourth listed auxiliary DT). In this case, the main difference would be that the solar modules can't cause wake effect on other solar modules (technically, they can, but that isn't relevant for their production power), but they can affect them in another way. For instance, one of the modules could cast a shadow that would reduce amount of sunlight that reaches other modules. This kind of shadow is also not constant, but depends on a number of parameters such as the season, the time of day, slope of the field (or roof) on which the modules are set, and so on. This would make it borderline impossible (and certainly rather impractical) to make a DT of the single solar module and then try to make a solar park DT out of that by multiplying the production of the single module by the number of modules and reducing that to take note of the shadows and other mutual effects. For this to be avoided, it was decided that the best approach would be to develop separate DTs, one for park and one for module, and then select the one to be used for the forecasts based on the case in question.

4 Use Cases in the Bulgarian Pilot

It has already been noted that the focus of the work that was conducted by the Bulgarian partners was on the two tasks assigned to them. Nevertheless, to successfully demonstrate the accuracy of the developed methods, it was necessary to pick an appropriate number of the Use Cases, covering wide range of scenarios that could happen and in which the solutions foreseen in the pilot could be helpful. The selection of the number of Use Cases (UC) had to be done carefully, as too high of a number could dilute the points intended to be made. On the contrary, too low of a number could leave some points outside of the scope of work, thus harming the worth of the entire pilot. After thorough consideration, a total of ten Business Use Cases (BUCs, concentrated on illustrating novel approach or demonstrating new technique for resolving some issue) and four System Use Cases (SUCs, focusing on the single step or a part of the process) was chosen. Some details on each of them can be found in this chapter, with each of the subchapters in it being dedicated either to a single BUC (first 10) or to a single SUC (last 4).

4.1 BUC 01 – Data Exchange between the Digital Twins

The first Use Case that was considered in the Bulgarian pilot was the one that focused on enabling data exchanges among different DTs. This BUC was envisaged in a way that allowed the automatized information flows between the Digital Twins, putting focus on precision and efficiency of the exchange process. This was particularly important for communication between the ANN-trained Digital Twins and the four major DTs in the pilot. The flow of the process is given in the figure below, in which each of the potential actors in the pilot (and, as such, in an energy sector) is presented in a separate column.

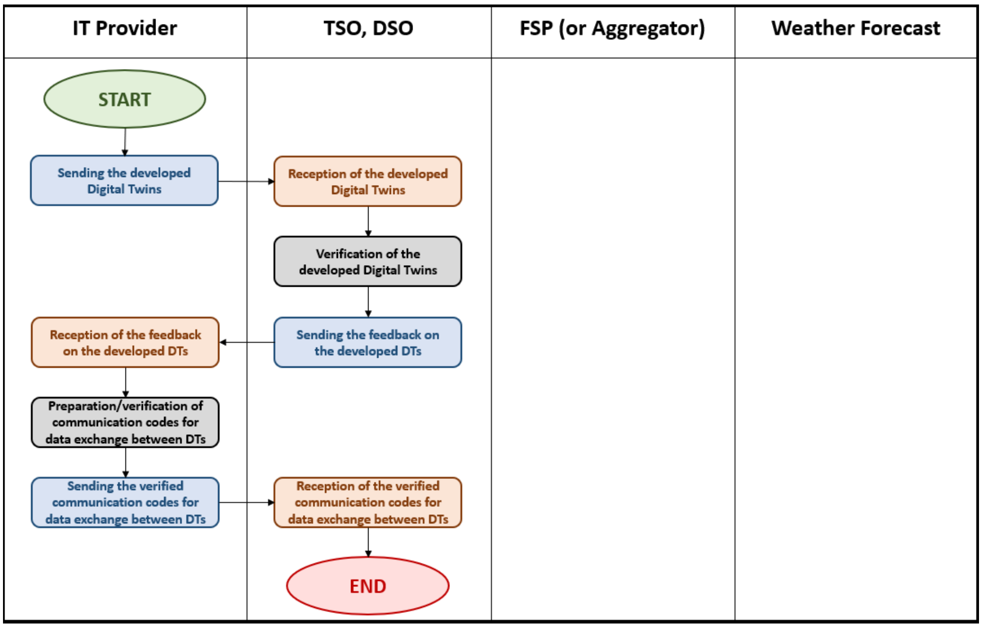


Figure 4-1 – BUC 01 – diagram of the process flow

Regarding the scenario that was considered here, it should be clarified that was not a scenario per se, as the BUC covered the general topic of the communication between DTs. This, however, made it a perfect fit for almost every possible scenario that could happen in real-life operation of the grid and a direct precondition for all of the remaining UCs. The codes drafted for the inter-DT communication are a strong tool for data exchange and creation of the entwined system model of desired accuracy.

4.2 BUC 02 – AI-Improved Forecast of WPP Production

The second BUC of the Bulgarian pilot was the one that concentrated on using the ANNs and high-resolution weather forecasts in order to improve the forecasts of production of the wind power plants (WPPs). This was achieved by applying the ANN-trained Digital Twins, where the special attention had to be on the DTs of the individual wind turbines and the DTs covering wind farms from the generation forecasting point of view. The purpose here was to improve the potential utilization of these facilities for the grid-related goals. This was done in order to give operators a better insight into the capabilities of generation units and chosen flexibility service providers in their grid and help them in managing the grid under their control safely and cost-efficiently. Process diagram for this BUC is given in Figure 4-2.

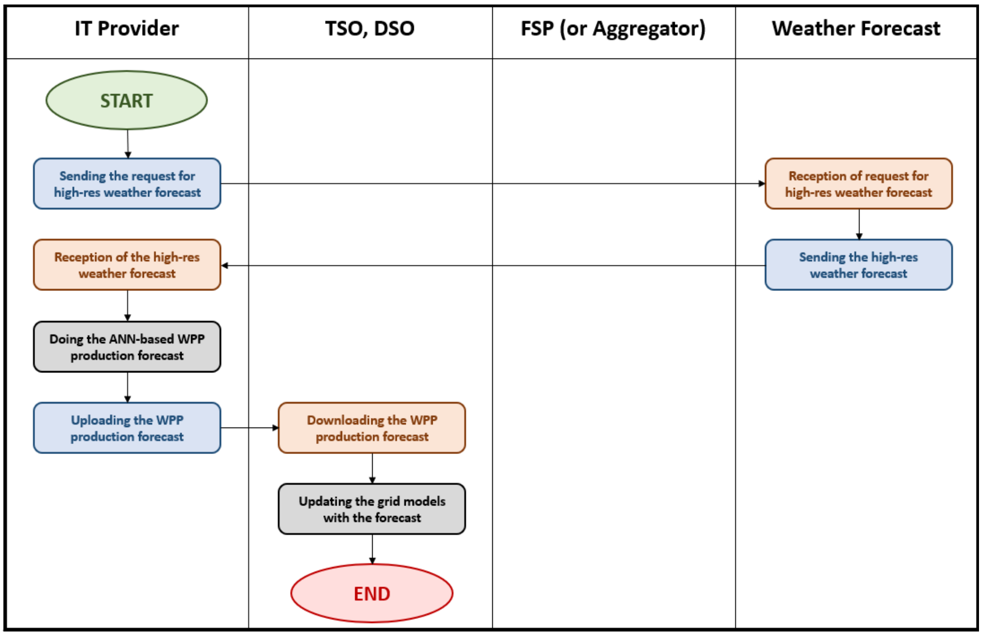


Figure 4-2 – BUC 02 – diagram of the process flow

The scenario that was examined in this BUC included the situation in which the system operators (SOs) want to improve the manner in which forecasts of the WPPs' production powers are performed. For that to be achieved, SOs would grant the IT provider access to the necessary set of input data to develop and verify the accuracy of ANN-based forecasting tool. This also stands for appropriate ANN-trained DTs that would have to be developed. In case in which insufficient amount of data or sufficient amount of data of lower quality would be available, this task would not be completed properly. This is true for both the technical parameters and for the climatic data. Reason for this can be found in the fact that one part of the delivered information has to be used as the training set for ANN, while the remaining part represents the information on which the developed tool can be tested up until the desired level of accuracy is reached. Of course, in order for all of these steps to make any kind of sense, the set level of accuracy needs to be very high. This tendency was also reflected in a way in which the success of BUC was verified. Namely, once the ANN-based forecasts became completed and available, there was a need to prove that they represent an improvement over the commonly used forecasts. This was done by comparing the obtained forecasts with reference values from the literature covering this topic. More on the results that were obtained by the forecasts and on the measure of the error made by the ANN-trained tool for wind power forecast can be found in Chapter 6 of this deliverable.

4.3 BUC 03 – AI-Improved Forecast of SPP Production

The third BUC of Bulgarian pilot was actually rather similar to the second one. However, the focus here was on the different kind of technology. This BUC once again concentrated on using the cutting-edge ANNs for the improvements of the forecasts of the production powers of the selected units. This time, however, attention was on the solar power plants (SPPs), which was achieved by using auxiliary ANN-trained DTs for solar modules and solar power parks. As a reminder, it should be stated that both of these were necessary to be developed as using one over another could prove to be better in some cases of interest, whereas another one could be preferred in other situations. This enhancement was selected as the focal point since it was deemed able to give the SOs clearer image of the potential flexibility service providers (FSPs), while also giving them the possibility to evaluate offers for services sent by those FSPs. This BUC can also be represented by flow diagram, as shown in the figure below.

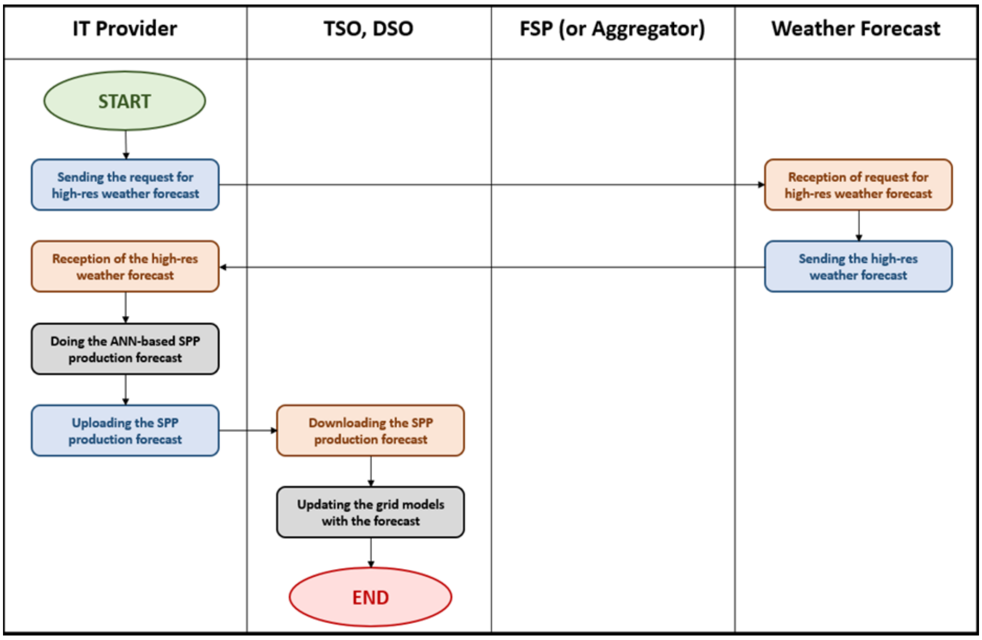


Figure 4-3 – BUC 03 – diagram of the process flow

In accordance with the description provided before the figure and the elaboration of scenario that was referring to the demonstration of BUC 02, the scenario that was considered in this case included the situation in which SOs decide that there is a need to upgrade the way in which the forecasts of the SPPs' production powers are performed. For this to be done, SOs would need to give the IT providers the necessary input data to develop and verify the accuracy of both the ANN-based forecasting tool and appropriate auxiliary DTs based on those ANNs. The quality of this information is once again of vital importance for the proper performance of this process. In the scope of this pilot, this was also of that same relevance for the success of all upcoming steps, as this Use Case (together with the previous one and the following one) was precondition for the proper preparation of the intertwined model of Bulgarian grid. This model was in turn needed for the BUCs which will be described later. Again, one part of the data had to be used for training of the ANN. The other part represented the information on which created tool was tested until the desired high level of precision was reached. Once the ANN-based forecasts were done, there was a need to prove if they really represent an improvement over commonly-used forecasts. This was done by comparing the forecasts with the values from literature.

4.4 BUC 04 – AI-Improved Forecast of OHL Ampacity

The fourth Use Case of the Bulgarian pilot was also the final one that dealt with utilizing cutting-edge techniques for forecasts' improvements. Nevertheless, unlike in the previous two UCs, the centrepoint of this UC were the ampacities of the OHLs and the comparison of the forecasted and static ampacities of the selected lines. This was accomplished with ANN-trained DTs for the OHL ampacity forecasting, which had to be made carefully, while taking into account both the relevant technical and mechanical characteristics of the line (diameter and cross-section of equipped conductors, height of the towers, rated voltage levels of the OHLs, etc.), and geographical and climatic properties of the terrain across which the route of the selected lines went (wind speed, irradiation, wind direction, temperature, etc.). All of these were necessary to adequately estimate the possibilities of cooling down the line during its operation, which directly affect the forecasted rating of the line. Flow of the process here is similar to the ones already provided for BUC 02 and BUC 03. It can be seen in the flow diagram shown below.

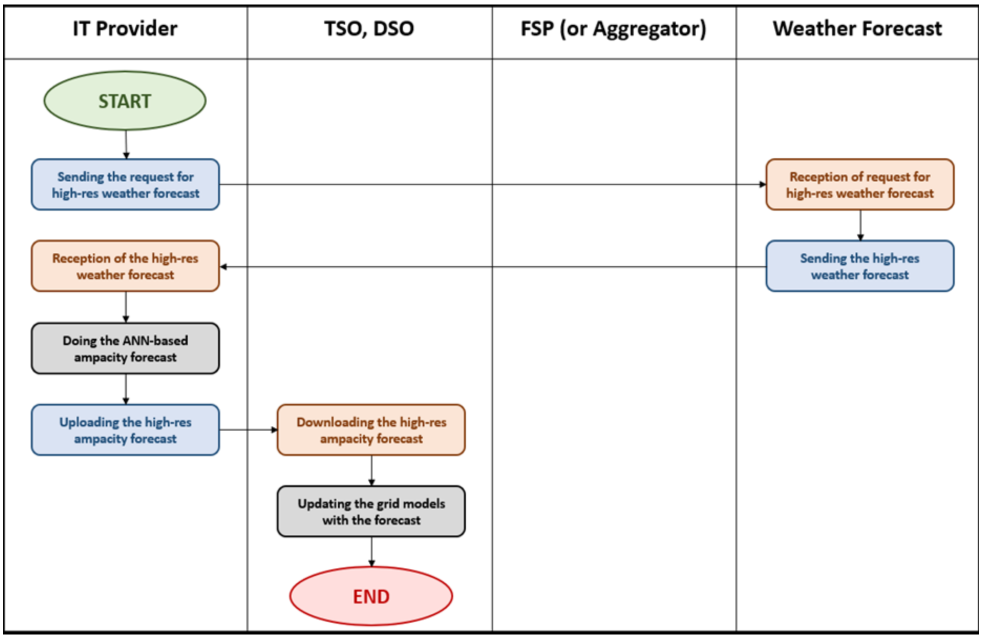


Figure 4-4 – BUC 04 – diagram of the process flow

The scenario that was considered in the scope of this BUC was based on the potential decision of the system operators to examine moving on from the seasonal line ratings and on to the ampacity forecasts. The necessary forecasts would then be conducted by considering climate parameters along the routes of the selected lines and the impact that those parameters may have on the cooling and heating of those lines. For example, one of the most important parameters is the wind speed in the direction perpendicular to the line, since this is the component of the wind that actually reduces the temperature of the surface layers of the conductors. For ampacity forecast to be conducted, system operators would need to give the IT provider the input data. This set of data would, together with the high-resolution numerical weather forecasts, be a base upon which the forecasts of ampacities could be performed by the ANN-founded tools and auxiliary DTs developed for this goal. As the manner of proof that this approach actually represents an improvement over the currently used seasonal ratings, the forecasted values would have to be compared to the actual seasonal ratings used by the respective SOs. This exact approach was also the one suggested for the verification of the outcomes of this BUC.

4.5 BUC 05 – Power Flow Increase on Cross-Border Lines

The fifth BUC was a continuation of the activities done within the BUC 04, since it also dealt with the forecasts of the OHL ampacities. The difference was, nonetheless, that this BUC concentrated on the cross-border lines, again utilizing DTs for the OHL ampacity forecasts based on EHV-HV DT and on the cross-border energy exchange DT. Another important part the needs to be highlighted here is that the capacity of the cross-border line depends on the operators on both sides of that border. In case in which one of the operators decides to use suggested approach, while the other operator still stays at the standard approach based on the static rating values, there will be no direct benefit from approach in question. However, for this BUC, an assumption was made that both affected operators decided to apply forecasted values of the ratings. In line with the fact that this case builds upon the foundation that's been laid in BUC 04, its diagram, given below, includes the forecast directly taken from that UC.

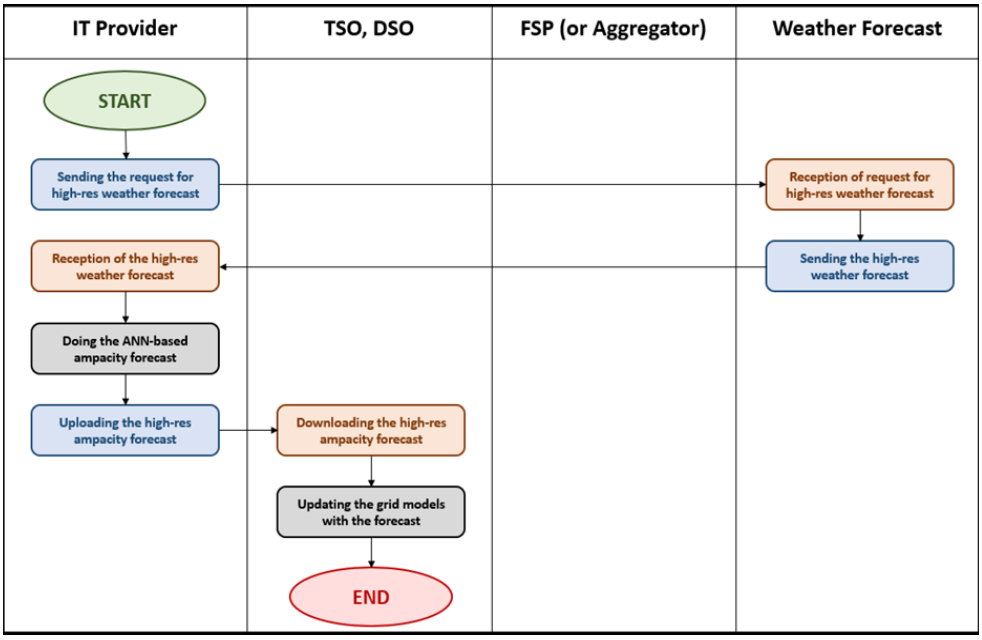


Figure 4-5 – BUC 05 – diagram of the process flow

The same logic indicated that the scenario selected for this process needed to represent a logical continuation of the scenario that was considered for BUC 04 of the Bulgarian pilot. As a reminder, that is the case that dealt with the enhanced ampacity forecasts of overhead lines in the grid based on the climatic parameters and their distribution along the selected lines. The scenario that was created for BUC 05 narrowed down the targets of those forecasts further to the list of tie-lines and/or the critical elements included in cross-border exchange. Once list of lines of interest was created, the IT providers could apply the same auxiliary ANN-trained DT for ampacity forecast from BUC 04 to determine the actual capacities of the designated lines in the defined period. If these forecasts would be delivered to the SOs, they would be able to update their simulation models based on these new ampacities. It is important to notice that this suggestion could impact both the market simulations (as the transfer capacities between the systems represent inputs for the market model) and the network simulations (as the ratings need to be inserted for each line in the grid). In addition to this, SOs would be capable of running calculations and determining benefits that could be achieved if realistic ampacity forecasts became the standard principle instead of the common seasonal transfer limits of the overhead lines.

4.6 BUC 06 – Locations for RES Connections' Optimization

The sixth BUC focused on the capabilities of high-voltage grid to host renewable energy sources in selected areas with substantial potential for the development of this type of generation capacities. The potential was estimated in coordination with Bulgarian TSO and based upon their experience and on the estimation of the climatic parameters in the different regions of Bulgaria. As can be concluded, this BUC was directly related to Task 7.5 of the TwinEU project, with the goal of the UC almost perfectly matching aim of that task. In this BUC, the optimization algorithm had the main function of locating optimal connection points for defined set of RES and storage capacities, all while considering interests of investors (thus enabling their facilities to operate without limitations), the SOs, the end consumers, and power system as a whole. Before the diagram of the process envisaged here gets shown, it should be emphasized that this is also the first of the BUCs in which some analyses were done by utilizing the DTs that have previously been updated with the forecasts determined in the previous four BUCs. With this out of the way and in the clear view of the reader, the flow diagram is provided in the next figure.

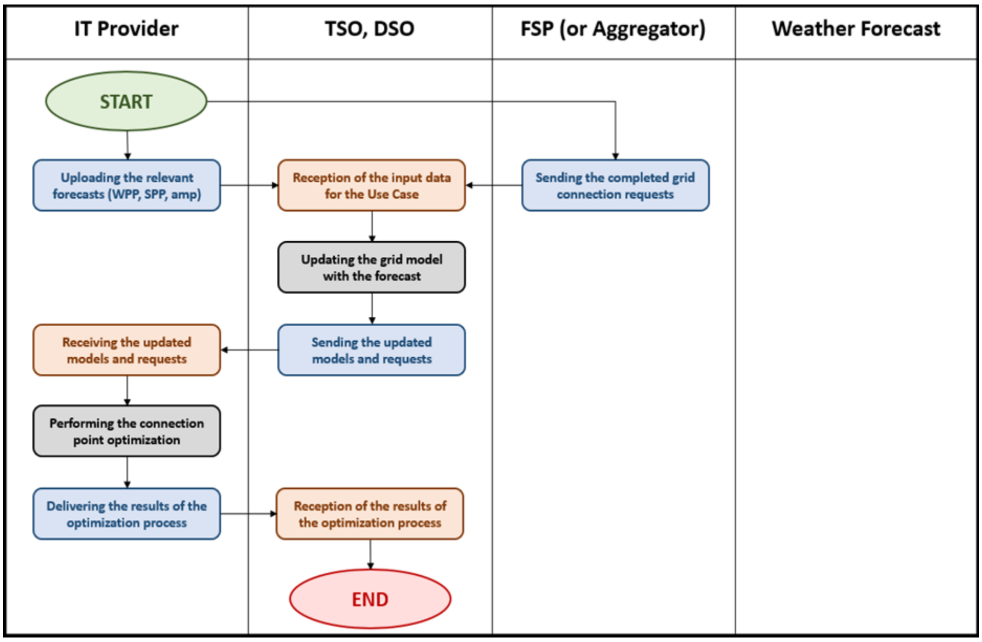


Figure 4-6 – BUC 06 – diagram of the process flow

The scenario relevant for this case considered the situation in which the IT provider completed the forecasts that are listed in the BUCs 02, 03, and 04. At that time, system operator in this case would get the requests for connection of larger capacities of RES and energy storage facilities in one of the regions for which these enhanced forecasts are available. In order to make the decision regarding the connection points of those capacities, system operator would ask IT provider to run the optimization procedure, taking both the interest of that system operator (by utilizing the realistic limits of transfer capacities), and the interest of the clients that submitted the request for connection (by ensuring the uninterrupted work of their respective facilities during the observed time-period). Once the results of the performed optimization procedure become available, IT provider would then upload them to the predefined location from which the SO would download them. Afterwards, the provided connection points could either be used as the assumptions for some of the internal analyses conducted within the system operator or could even be forwarded to the clients, depending on system operator's decision.

4.7 BUC 07 – N-1 Assessment on the DT level

The seventh BUC that was analysed focused on the reliability of transmission system in Bulgaria. It was done by running N-1 assessment, which is the kind of analysis in which the single outages of every grid element were tested, all while monitoring the impact that each and every of the outages has on the elements that remain operational. Results of this analysis typically give the SO insight into severity of outages and help with the planning process. This BUC has been completed by simultaneously using EHV-HV DT and ANN-trained DTs for wind parks, solar parks, and ampacity forecasting in the process. Namely, auxiliary DTs were used to generate the forecasts of the needed inputs for the major DT, after which the major DT was updated to include the forecasts. This is why BUCs 01-04 represented a direct precondition for the successful run of this BUC. The flow of the process is provided in the figure below.

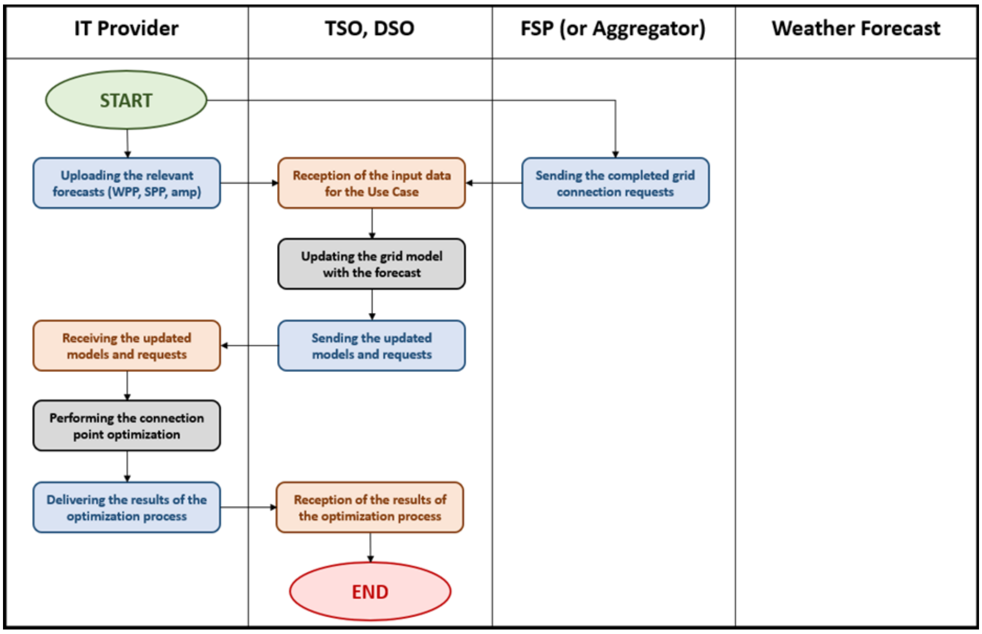


Figure 4-7 – BUC 07 – diagram of the process flow

The scenario that was observed in the scope of this BUC took into account the situation in which system operator would decide to improve the way in which the N-1 assessment of the grid operation is performed. For that to happen, they would give IT provider basic information regarding the system regimes that may be critical from technical point of view (focusing on the or in which the lines can get overloaded). For instance, the selection of regimes could include the ones in which the consumption in the system is at peak, as that can cause high loadings of the critical lines, or the ones in which the RES work with the power close to the rated one, since that can cause unpredictable flows of the energy in the grid. IT provider would then apply the ANN-trained DTs for forecasts (created and tested before in the scope of BUCs 02-04) to determine the key parameters of the grid's operation more efficiently and accurately compared to the methods that are commonly used in the operators' work. Once that would be done, system operator could update the simulation models based on the enhanced forecasts and conduct the standard N-1 analysis. With that out of the way, system operator would also be able to perform verification of the results obtained by the application of these models and to decide upon the further course of action that would need to be taken to mitigate or resolve issues. The measures could also be tested, with them varying from switching operations to building the new infrastructure.

4.8 BUC 08 – DT-based Maintenance Plan of TSO Grid

The eighth BUC that will be described was foreseen as the successor of UC7, including N-1 analyses of TSO grid once again. However, the difference was in the fact that some grid elements were treated as “under works” this time. This is a completely realistic situation, since the works on maintaining the grid need to be spread throughout the year according to the predefined plan. During the works, there could be several critical situations in the grid, either caused by the demand variations, which could go from very low to rather high, or by the operation of the variable RES. These swift changes of the system operating conditions could cause effects that were not foreseen adequately and harm the reliability of the entire grid in the process. The estimations made here could aid the TSO in scheduling the grid maintenance, again utilizing the EHV-HV DT and ANN-trained DTs for wind power plants, solar parks, and OHL ampacity forecasting. Of course, in order for this BUC to be possible, BUCs 01, 02, 03, and 04 had to be done beforehand, as they were preconditions for this UC. The flow of BUC 08 is given below.

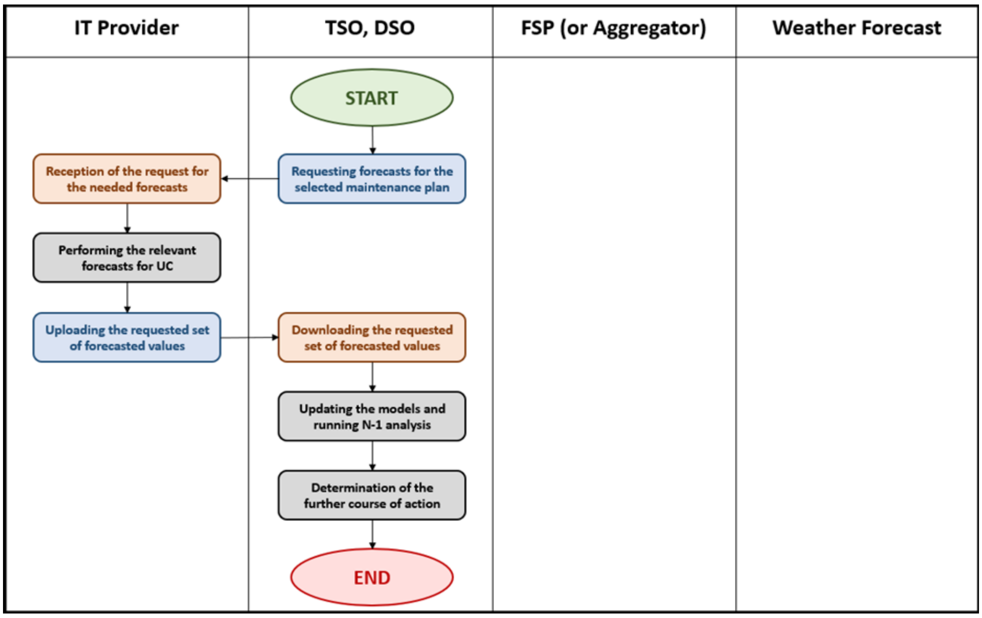


Figure 4-8 – BUC 08 – diagram of the process flow

The scenario took into account the situation in which the SO desires to check the maintenance plan by running the N-1 assessment for the state of the system under maintenance. For that to happen, they would give the IT providers basic information regarding the critical system regimes (regimes in which, for example, voltages could go out of the range or the lines could get overloaded), determined so that they are relevant for the season enveloped by the maintenance plan. Those could be regimes in which the demand is at the extreme levels or the regimes in which the wind or solar plants produce energy with the capacity near the rated value. IT provider would use the ANN-trained DTs for forecasts (created and tested before in the scope of BUCs 02-04) to calculate the crucial parameters of the grid’s operation. After that, the system operator could update the simulation models based on the enhanced forecasts and perform standard N-1 analyses of the grid while taking into the consideration predefined maintenance plan. With that taken care of, SO would be able to verify results obtained by utilizing the models and also to determine the further course of actions that need to be taken in order to mitigate or to fully remove the problems that were noticed during the analyses. Out of the proclaimed goals of the TwinEU project, this will contribute to security of the system and to the reliability of energy supply.

4.9 BUC 09 – Flexibility Requirements to Avoid Congestions

The ninth BUC in the Bulgarian pilot focused on one of the ever-present problems in the grid operating business, which is the mitigation of the congestions that occur on the lines. For that to be illustrated, congestion in the DSO grid was simulated, for it to be resolved by using resources that are connected to the DSO grid. Of course, the selection of the region of the distribution grid that suits the assumptions needed for this case was performed in tight collaboration with the DSO partner, where the particular attention was given to picking the area of the grid in which the high enough capacities of the renewable sources exist (or are set to exist in the upcoming years). This BUC utilized MV DT and ANN-trained DTs for wind parks and solar parks, with auxiliary DTs again providing necessary inputs for the updates of the major involved DT. In line with its proclaimed targets, this case demonstrated the ways in which the distributed flexibility service providers could help the grid in risky operational regimes and the ways in which the enhanced forecasting could assist in this task. Once again, diagram in which the flow of the envisaged process can be seen is provided, in the shape of the figure below.

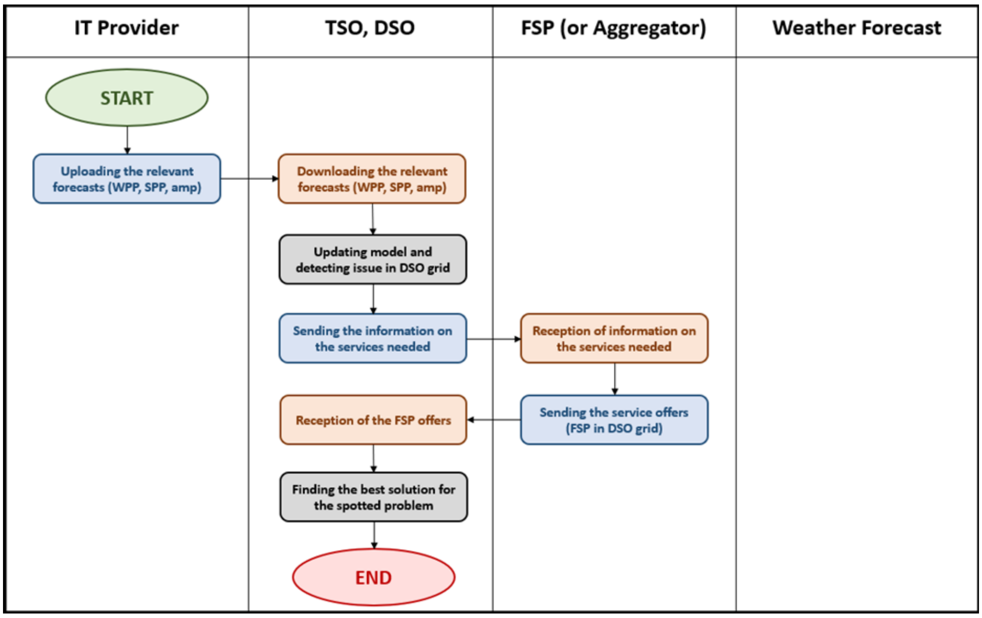


Figure 4-9 – BUC 09 – diagram of the process flow

The scenario that was taken into account simulated the situation in which the congestion is spotted in some region of the distribution grid. Of course, as it was already stated, this area of distribution grid would have to fulfil one condition – it would need to have sufficient amount of the service providers connected to the distribution grid. The type of these providers may vary depending on the observed area, so they could be the WPPs, they could be SPPs, they could be storages, or they could be load that can be controlled by the system operator in order to provide the flexibility to the grid. In order to mitigate the problem and prevent undesired consequences, system operator would ask the flexibility service providers to offer the services that may help. The offers would later on be evaluated by using the models updated by the forecasts of relevant system parameters (done in the scope of some of the earlier BUCs of the pilot, either 02 or 03). This would allow the DSO to evaluate the potential that each of these service providers has for resolving the congestion and enhance the reliability of the foreseen mitigation measures. That would greatly improve the quality of the energy delivery to the customers and increase grid resilience, corresponding to the vision of TwinEU project and its primary listed goals.

4.10BUC 10 – Inter-SO Flexibility Exchange

The tenth BUC of the Bulgarian pilot was rather similar to the one preceding it, as it also dealt with the issue of some of the lines in the grid potentially getting congested in some of the operational regimes. In order to understand the difference between the two, one could start from the fact that, in BUC 09, the congestion in the distribution grid was resolved by utilizing the resources that were connected to the distribution grid as well. Basically, the problem in the certain part of the system was mitigated by using the resources that are connected to that very same part of the system. In the BUC 10, however, the focus was on resolving transmission grid congestion by using resources that are connected to DSO grid, thus highlighting the potential for the cooperation and coordination between the SOs in the critical situations for the system. For that to be accomplished, EHV-HV and MV DTs were used, as well as all auxiliary ANN-trained DTs listed in Subchapter 3.5. Once again, BUCs which had to be completed beforehand were BUCs 01- 04. The flow of the process of BUC 10 is given in figure below.

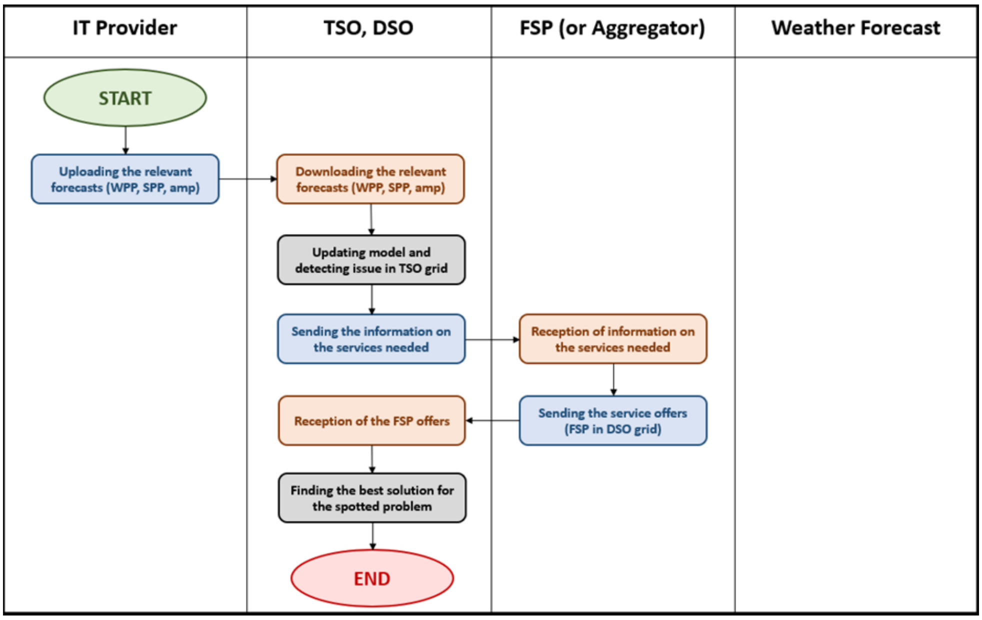


Figure 4-10 – BUC 10 – diagram of the process flow

The scenario that was considered for this case simulated the situation in which the congestion is spotted in some region of the transmission grid. Similar to what was explained in the BUC 09, this area of the grid needed to fulfil one condition – it had to boast the sufficient amount of flexibility service providers connected to the distribution grid. The type of these providers could vary depending on the observed area, so they could be the wind plants, they could be solar plants, they could be the storages, or they could be demand that can be controlled by the distribution system operator in order to provide the required amount of flexibility to the grid. In order to mitigate the spotted problem and to prevent the imminent consequences to the grid, TSO could reach out to DSO who would then ask the flexibility service providers to offer their services that might help. Offers could later be evaluated by using the models updated by the forecasts of relevant system parameters (performed as part of the earlier BUCs of the Bulgarian pilot). This would allow the SOs to evaluate the potential that the flexibility resources connected to DSO grid have for resolving the congestions in the transmission grid and to improve the reliability of the planned mitigation measures. That would, in turn, improve the quality of the security of energy supply to the consumers and increase the grid resilience for the sake of reliability of its work.

4.11SUC 01 – Integration of AI-Improved Forecasts into DTs

Before moving on to the actual description of the first SUC that was defined within the Bulgarian pilot, one should briefly be reminded of the differences between the BUCs and the SUCs, already mentioned in the introductory part of this chapter. Namely, BUCs that were described in the previous ten sections were focused on illustrating entire aspects of the developed solution. On the other hand, SUCs which were proposed served as an extension of a single step or, at most, several subsequent steps in process for which it was estimated by the partners that they need to be elaborated in more details. Regarding the first such SUC in the Bulgarian pilot, it was focused on the integration of ANN-enhanced forecasts into the grid DT and running an analysis on such a model. The flow diagram of this SUC is given below, in the Figure 4-11, created by utilizing the same template that was already used for all defined BUCs.

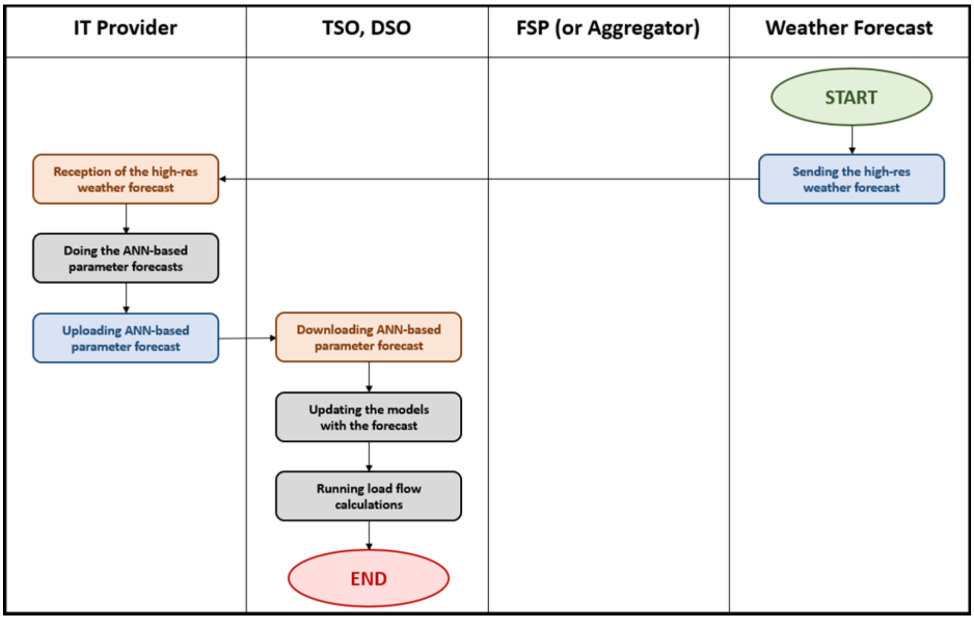


Figure 4-11 – SUC 01 – diagram of the process flow

This SUC was done from the perspective of the TSO employee which desires to integrate the newly obtained ANN-boosted forecasting algorithms into the modelling and calculations process. From the technical point of view, it focused on continuing where BUC 01 left off, with all codes for data exchange between DTs being completed. Building on top of that, this SUC's scenario expanded that by including the demonstration of what could the grid DTs that were subjected to those codes earlier be used for. In line with that, it is rather clear that the situation described within this SUC does not happen strictly before or after the scenarios of the BUCs. On the contrary, it happens in the middle of those. Namely, for the SUC 01 to be run properly, there was a need to complete BUCs 01-04 beforehand. On the other hand, SUC 01 was also a basis for nearly all calculations that were performed in the scope of BUCs 07-10. In a less direct manner, it was also connected to the assessments done in the optimization cycles conducted within the work performed in the BUC 06, since the calculation of the measure of solution there also needed to incorporate the automatic running of the load flow calculations on the EHV-HV DT. Even though the analyses which were done there did not directly include the forecasts conducted by auxiliary DTs, the codes used in that BUC had a lot of common lines and details as the ones shown in SUC 01. This can also be seen as an additional proof of how intertwined the Use Cases in Bulgarian pilot were in order to give different perspectives of the solutions developed for the declared targets.

4.12SUC 02 – TSO-DSO Energy Exchange Estimation

In accordance with the mentioned topic of the Bulgarian pilot attempting to give all-encompassing view of the situation and the improvements that have been achieved by the work invested by partners in it, it only made sense to give a different point of view in the second SUC than it was the case in the first one. Hence, this SUC switched perspective to the one of the DSO employee and concentrated on one of the topics that are becoming more and more interesting by day, especially in the circles of the system operation – the topic of energy exchange between the TSO and DSO and reverse flows, where the energy goes from the DSO grid to the TSO grid. This is a point that could at the same time represent both a reason for concern, since this type of flows was not seen much before the last couple of years and it completely switches the paradigm of the way in which the power system as a whole functions, and as an opportunity that should be seized, since this opens the door for the TSOs to utilize even the resources that are connected to the distribution grid (as it was already discussed in the subchapter on the BUC 10). The flow diagram of the process observed within this SUC can be seen in the Figure 4-12.

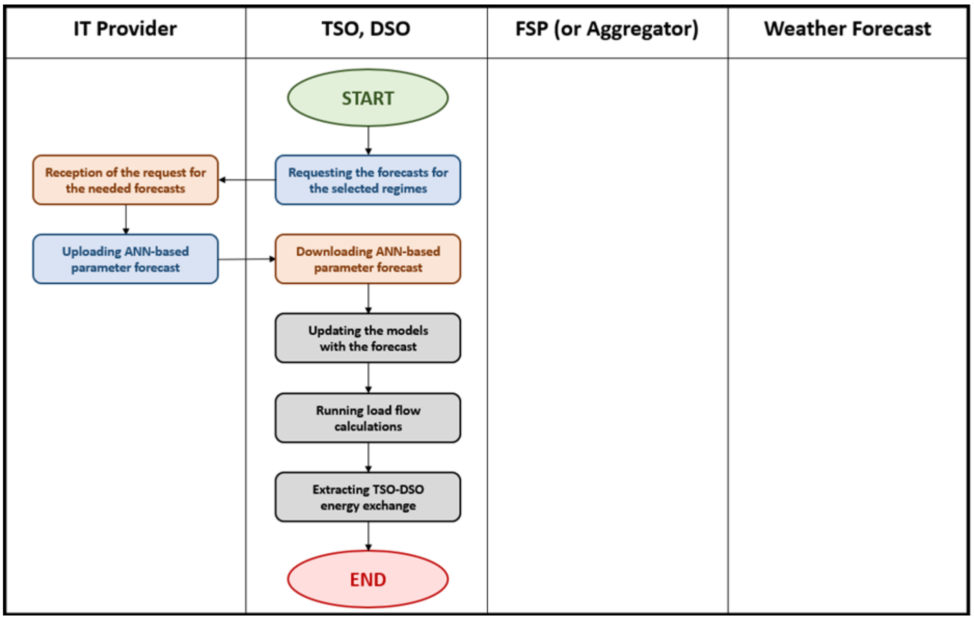


Figure 4-12 – SUC 02 – diagram of the process flow

In order for this to come to be, this SUC observed a scenario in which the DSO wants to determine the flows in the part of the grid supplied from one single substation, with the particular spotlight being on the energy flows through transformers in that substation, as these transformers are what connects TSO and DSO grid. The flows would be determined by utilizing the ANN-founded forecasts of the WPP and SPP production powers and the known demand profiles and variations to update the MV DT and provide a solid basis for this analysis. Flows in question would not only give the information about the energy exchange between TSO and DSO through observed substation (which, as already mentioned in the paragraph preceding the figure, can even be crucial for TSO in some of the more extreme cases), but it would also give an insight into the loading of transformers in the observed substation. This could serve as an indicator of whether those transformers could get overloaded, which is essential to know in order to ensure security of the energy supply in the region of interest. To take matters even further, if those transformers would get overloaded in significant number of hours, that could be a signal that their replacement could be necessary to accommodate the grid to the expected operating conditions.

4.13SUC 03 – Impact of AI-Forecasted OHL Ampacity

Although two out of ten BUCs of the Bulgarian pilot were dedicated to the OHL ampacity and the forecasts of those parameters done by the particularly trained ANNs, it was noticed that there was no UC that would focus on demonstrating the impact that this can have on the more reliable observation of the system. More reliable observation here means proper detection of problems and congestions, while avoiding the false positive signals that would be a consequence of the too conservative approach dictated by the application of static line ratings. That is the gap that was bridged by SUC 03. For this task, the point of view was once again shifted to the one of the TSO (similar to what was done in SUC 01). This time, however, the focus will be on running the load flow (or N-1) calculations in two different cases – one in which the OHL ampacities were taken as they are used in practice (i.e., static), and other one in which the ampacities of the affected lines were obtained from the forecasts performed by using ANN-based algorithms. The flow diagram corresponding to this process is given in the figure below.

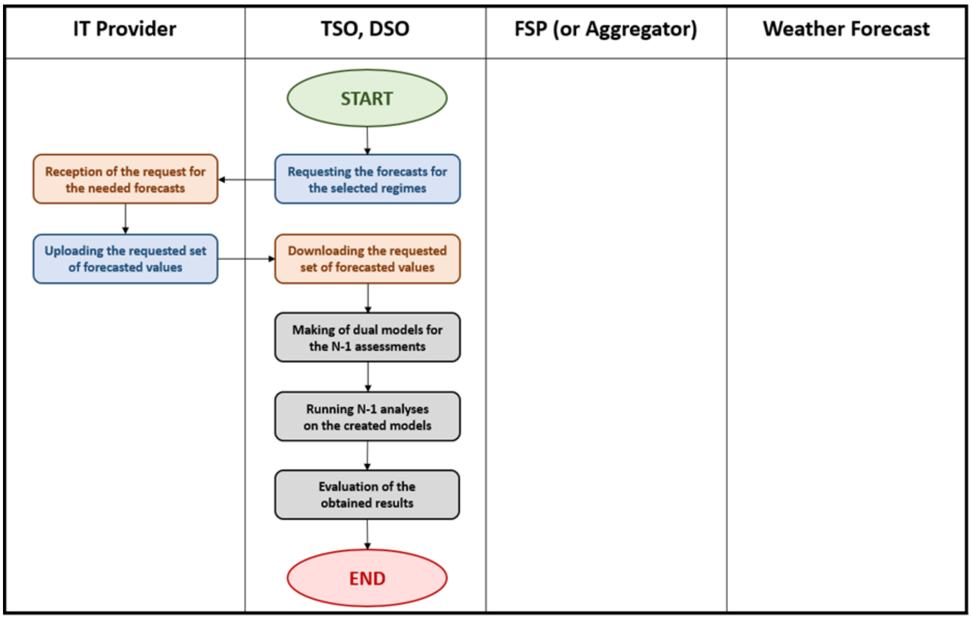


Figure 4-13 – SUC 03 – diagram of the process flow

It should be pointed out that, although the diagram specified that the N-1 assessment would need to be conducted, the exact same point could be made by performing the classical load flow analyses, as the target here was not to give a set of results that would be copied verbatim and used as a basis for some projects in the transmission grid. The point was rather on proving a concept and illustrating just how could the ANN-based forecasts alleviate some of the constraints in the normal grid operation. Hence, the scenario here took into account the situation in which the TSO would be willing to test the impact that the application of the ampacity forecasts could have on the results on the calculations. In order to do this, TSO would make two separate grid models – one in which the ratings of the selected set of lines are the same as static ones and the other in which the ratings of the selected set of lines are equal to the ones given as an output from the ANN-based forecast. After that, the desired analyses could be done on both of those models, with the differences in the results getting attributed solely to the variations of the line ratings (as all of the other parameters would be same). Those differences in the percentual loadings of the affected lines would be noted and then utilized as a foundation for the thorough discussion on the potential that this technique could offer in the everyday system operation.

4.14SUC 04 – Impact of AI-Forecasted OHL Ampacity

In order to properly understand the thought process behind this SUC, one would need to go back to BUCs 09 and 10, described in some of the earlier subchapters of this report. As a reminder, BUC 09 was the one in which the problem was detected in the DSO grid and the FSPs connected to that same grid were utilized in order to resolve that issue. On the other hand, BUC 10 had a different goal, which led it to consider the situation in which the congestion was spotted in the TSO grid and mitigated by applying the FSPs connected to the DSO grid, demonstrating the potential for the flexibility exchange between the SOs in the process. However, it is clear that both of these took into account only cases in which the available FSPs are connected to the single voltage level, whether it was the transmission or the distribution one. However, in the real-life operation of the system, a situation could occur in which some of the available FSPs would be connected to the transmission grid and the others would belong to the distribution system. Their respective impacts on some problem in the grid could vary depending on the location of the congestion, locations of the FSPs, technical characteristics of the grid, even time of day. This is why it was decided to simulate this situation as well, leading to the formation of SUC 04 of the Bulgarian pilot. The flow diagram referring to the described process is found in the figure below.

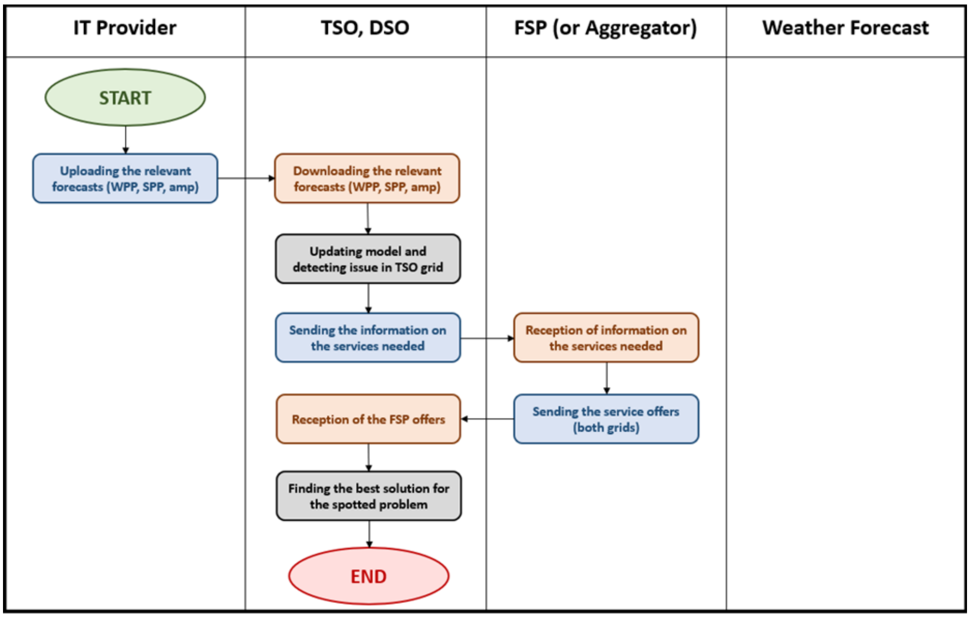


Figure 4-14 – SUC 04 – diagram of the process flow

Regarding the scenario considered for this Use Case, it was rather similar to the one envisaged for the BUC 10. In it, congestion would be spotted in some region of the transmission grid. Here, however, the condition that the region would have to fulfil would be having the sufficient amount of flexibility service providers connected both to the transmission and to the distribution grid. Type of these FSPs could vary once again, so they could be the wind plants, they could be solar plants, they could be the storages, or they could be demand that can be controlled by system operator (this was the only one out of FSPs that was reserved only for the distribution grid). In order to mitigate the congestion, TSO could use the ANN-boosted DTs to evaluate potential that each of the FSPs in the area has for resolving the congestion that has been seen, hence simulating the real-life situation in which a problem like this needs to be solved. When the selection would be done, clear estimation of the impact that the chosen FSPs have would be performed, with all of the noteworthy improvements underlined in the process.

5 Data Collection Process

As already explained in the Chapter 4 of this report, the work of Bulgarian partners focused on the ten BUCs and additional four SUCs that have been defined for it. However, in order to make any progress, a proper set of input data needed to be obtained at the start. This, first of all, required choosing the points of interest (PoIs) for which the data would be collected. After that, the questionnaire had to be developed by the IT providers (the ones in charge of doing the forecasts and proposing the DTs). This questionnaire was distributed to the partners in the project, marking the start of data collection. With the data collection completed, obtained information could be used to train and test the forecasting ANNs and, later on, to update the gathered models with those. This chapter will thus be dedicated to providing some details on each of these steps to make them as transparent as possible for the reader.

5.1 Criteria and Selection of POI

The first part of this entire process was the selection of the proper PoIs for which the data would be asked for from the relevant partners. The main target set before the selection was to enable the partners to investigate energy exchange effects on the interstate border between Bulgaria and Greece, as well as the effects of energy transit across the Bulgarian system. This allowed them to encapsulate the border-crossing congestions and the internal congestions that are caused by the energy transit as well, with the particular attention given to the influence of variable renewable sources production in the chosen areas of the Bulgarian grid. In line with that, three main criteria could be defined, each of these being both relevant for the proper operation of the system and tightly entwined with the efforts foreseen for the pilot. These three criteria (or impacts) that had to be considered in the selection process were:

- energy transit effects;
- cross-border effects;
- internal congestion effects.

Taking all of this into account, it was clear that, in order to demonstrate a cross-border impact, internal congestions, as well as energy transit effects, appropriate selection of points of interest needs to be made. It was deemed impractical (if not nearly implausible) to attempt to find a single area that could be utilized for illustrating all of these impacts, since that area would need, for example, both close to the border for the energy exchange effects to be visible and far enough from the border for internal congestions to become clear as well, all this while having the sufficient number of renewable sources for the improved forecasts to have an impact. With that in mind, it was decided to use three separate areas instead of trying to find a single one. The selection then came down to the following three areas:

- **Area 1:** WPP and SPP PoIs, and one tie line PoI near to the border with Greece;
- **Area 2:** WPP and SPP PoIs, and one tie line PoI near to the border with Romania;
- **Area 3:** Critical internal line in central Bulgaria (on transit way between Greece and Romania).

This selection that has been made can also be seen in the Figure 5-1 (below), where each of the three grey shapes corresponds to one of three areas that was described in the shown list. It would be worth mentioning that the North-to-South order of these areas does not match their accompanying numbers as the numeration was not done based on location, but on the order in which each of them was picked.

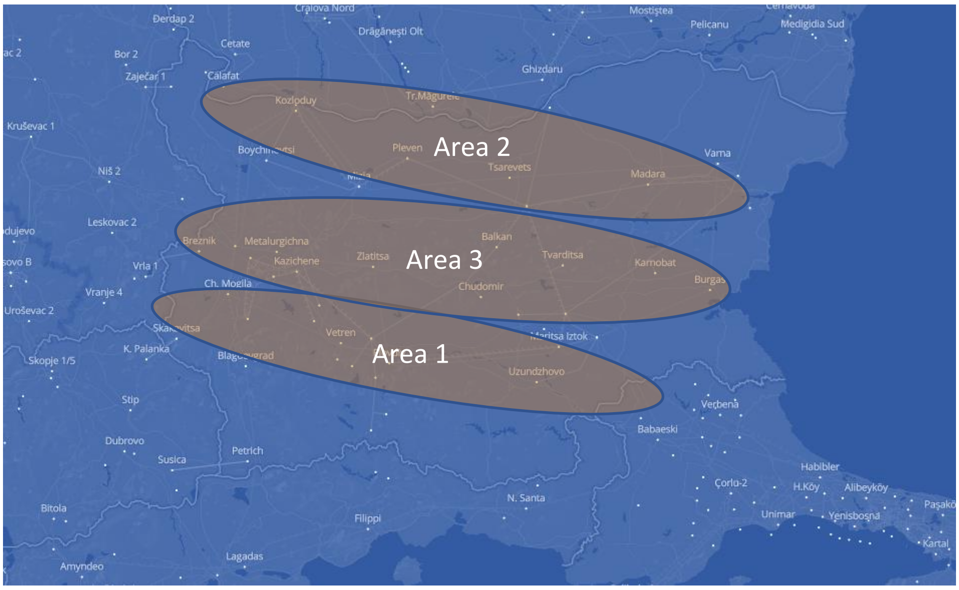


Figure 5-1 – Highlight of the areas of interest for the Bulgarian pilot

Of course, the data was not collected for every point in these three areas. Instead, the further filtering had to be done in order to handpick sufficient number of PoIs belonging to these areas to demonstrate the pilot achievements without harming the clarity of whole process by considering too many points.

5.2 Proposed PoIs in Bulgarian Transmission Grid

The first set of PoIs that had to be defined (and the most complex one as well) was the one referring to the transmission system of Bulgaria, with bilateral coordination needing to happen between the IT provider and the TSO partners. After deploying the data collection survey and having open discussion among these partners, following set of the regional PoIs in the transmission grid that would be further used for Bulgarian pilot had been identified. These points were used for the analyses, as will be shown in the later chapters of this deliverable. Proposed PoIs are, along with their respective types, enclosed in Table 5-1. In order to give proper context on why all of these were necessary, each of the selected points of interest will have a dedicated description in the continuation of this subchapter, followed by the map showing their locations in the Bulgarian grid. These maps will (particularly for the PoIs which are related to OHLs) also prove the importance of the PoIs for the regional and internal energy transits.

Table 5-1 – Selected PoIs for the Bulgarian pilot

Country	Type	Name
Bulgaria	Wind park	WPP Sveti Nikola
Bulgaria	Solar park	SPP Karadzholovo
Bulgaria	Interconnector - 400 kV OHL	OHL SS Blagoevgrad (BG) – SS Thessaloniki (GR)
Bulgaria	Internal 220 kV OHL	OHL SS Plovdiv – SS Aleko

5.2.1 PoI in TSO Grid 1: WPP Sveti Nikola

The first PoI that will be described here is the one that was used for collecting data related to the operation of the wind power plants in Bulgaria and for training and testing steps of developing ANNs utilized for enhanced forecasts of the production powers of the wind units. Since this was, as explained in Chapter 4, one of the main preconditions for all other activities in the pilot, it is clear just how important having the data for it was crucial. For that purpose, WPP Sveti Nikola, shown in the Figure 5-2, was selected.

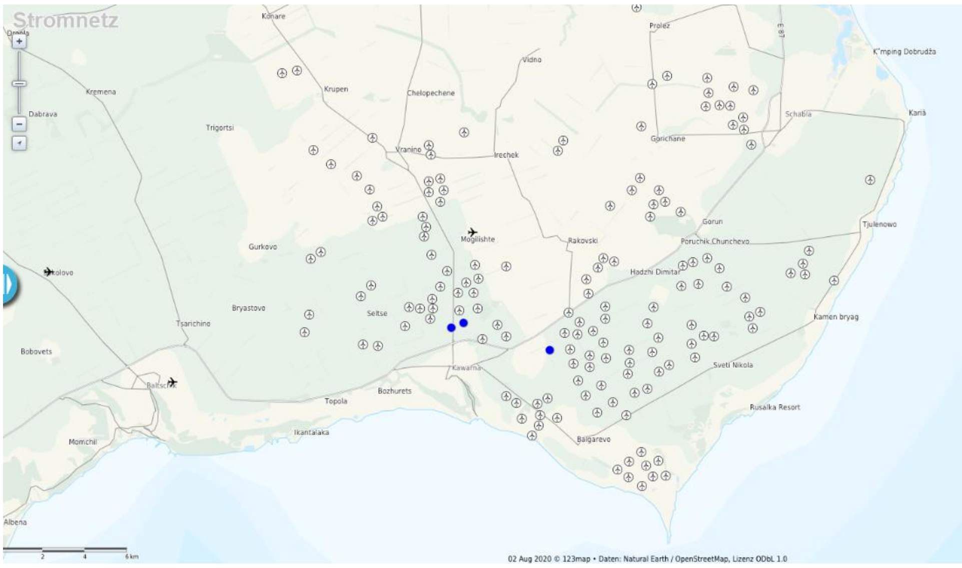


Figure 5-2 – WPP Sveti Nikola in Bulgaria

5.2.2 PoI in TSO Grid 2: SPP Karadzholovo

The second point of interest that will be elaborated is the one that was used for collecting data related to the operation of solar power plants in Bulgaria and for training and testing steps of developing ANNs utilized for enhanced forecasts of the production powers of the solar units. As this was also one of the main preconditions for all of the remaining activities foreseen in the scope of the pilot, any hiccups in data collection process could not be afforded. SPP Karadzholovo, shown in the Figure 5-3, was chosen.

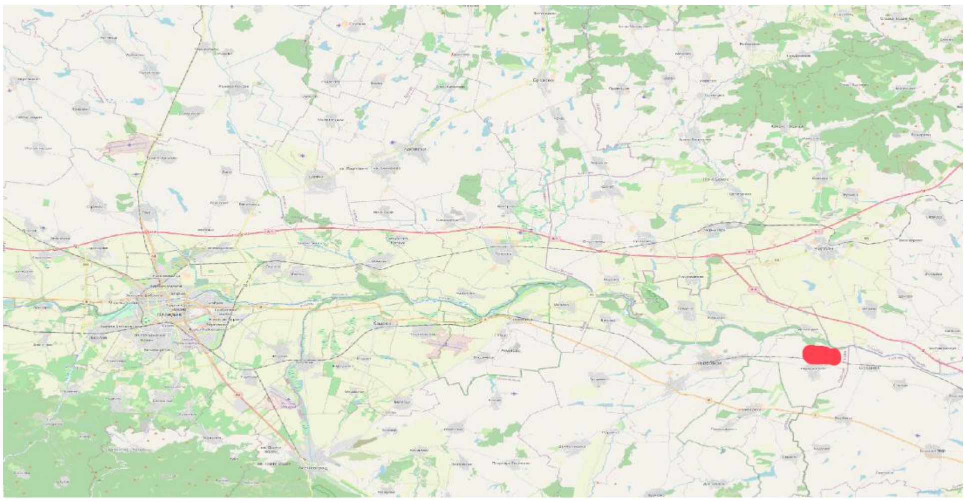


Figure 5-3 – SPP Karadzholovo in Bulgaria

5.2.3 PoI in TSO Grid 3: OHL SS Thessaloniki (GR) – SS Blagoevgrad (BG)

The next point of interest in the transmission grid of Bulgaria was the first one that could be used in order to illustrate the impacts of the ANN-based forecasts not only on the generation capacities, but on the grid elements and their operational conditions as well. The line that has been chosen here had to be picked in such a way to allow the proper evaluation of the effects that enhanced forecasts could have both on the ratings of the cross-border lines and on the energy exchanges between Bulgarian system and the systems around it. In accordance with all of that, 400 kV line from SS Blagoevgrad in Bulgaria to SS Thessaloniki in Greece was chosen. The map in which this PoI can be located is enclosed below.

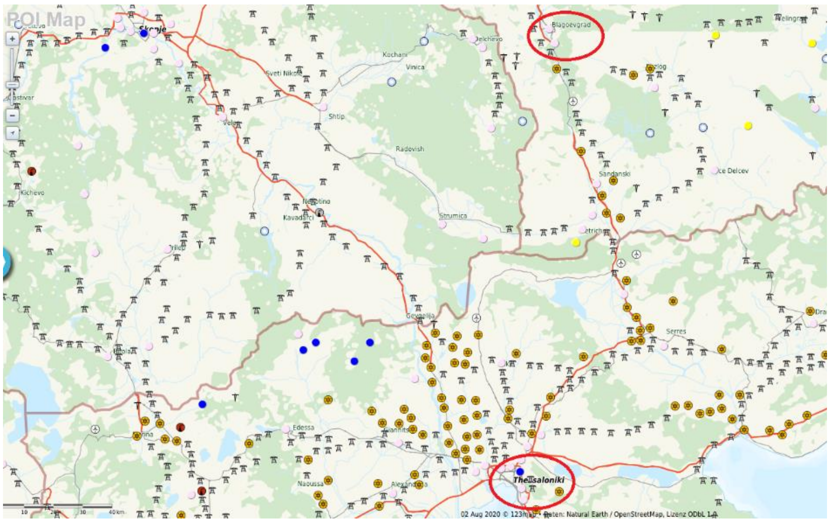


Figure 5-4 – OHL 400 kV SS Blagoevgrad – SS Thessaloniki

5.2.4 PoI in TSO Grid 4: OHL SS Plovdiv – SS Aleko

The final selected point of interest in Bulgarian transmission grid has been picked as one of the internal lines in the Bulgarian system that could become congested in cases in which the flows across it become high enough. This can either occur due to the transits of energy through the Bulgarian grid or due to the operation of the variable renewable energy sources in the areas connected by this line. The former would be the consequence of the strategic position of the Bulgarian system, whereas the latter would be assigned to the unpredictable flows dictated by the changes in the climatic parameters. Both made this line a good candidate for the demonstration of the ANN-based ampacity forecasts and the effects that their applications could have on the grid. Simplified presentation of the OHL route is given below.

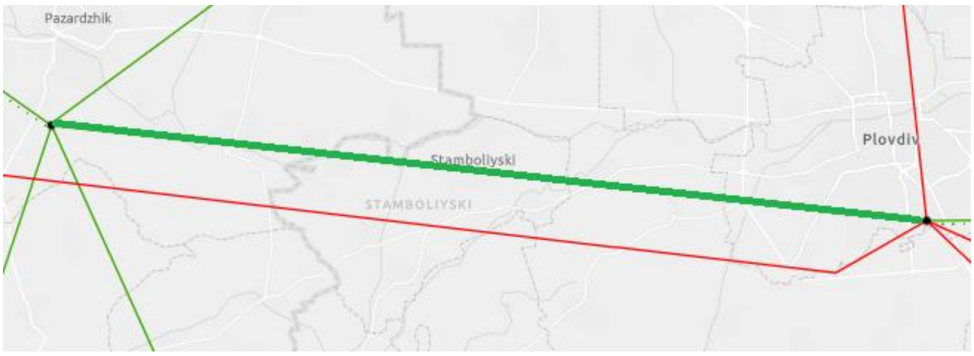


Figure 5-5 – OHL 220 kV SS Plovdiv – SS Aleko (in thick green line)

5.2.5 Fall-back Options in TSO Data Collection

Of course, a possibility also had to be considered that some of the requested information could not be provided by the partners from Bulgarian TSO. It was also clarified at the very start that this would not be due to the lack of willingness on their side, but due to one or both reasons that are listed below:

- information is not available – some of the information that would be good to have was out of the scope that the TSO typically requires before the initiation of the connection process, which could, for example, be the georeferenced location of each tower of the turbines in a wind power plant;
- information is confidential – some of the information could be referring to the confidential data related to the market behaviour and performance of individual clients connected to the grid; this could be overcome either by applying aggregation procedure for the clients in the same region, by anonymizing the information, or by using fictitious facilities based on the real-life parameters.

Therefore, there also had to be a Plan B for every dataset that could be moved on to if the information which is absolutely necessary also turned out to be unavailable. These fall-back solutions included, for instance, usage of the publicly available data and replacement of exact parameters by the appropriate typical values from the literature. The example of the former can be found in the Plan B for the precise locations of the wind park generator units and the OHL towers of the chosen lines that were foreseen to be extracted (in case of a need) from publicly available data on web portal: http://www.flosm.de.

5.2.6 Data Collection for Part of the Bulgarian Distribution Grid

Adding to data collection that was done for the transmission grid in Bulgaria, relevant information also needed to be obtained for the affected parts of the distribution grid in Bulgaria. Namely, it is clear that for some of the UCs this was the key set of information, as they focused specifically on using the MV DT and the flexibility resources that are connected to the distribution grid. To estimate the potential that these resources have, it was necessary to have a proper dataset related to them as well. Hence, the data collection regarding the part of DSO grid included following data, deemed to be vital for UCs:

- wind power plants in the affected areas – information regarding the total capacity of wind units connected to distribution grid, divided by individual units or by the consumption regions of the substations located in these areas, taking care of data confidentiality;
- solar power plants in the affected areas – information regarding the total capacity of solar units connected to distribution grid, divided by individual units or by the consumption regions of the substations located in these areas, taking care of data confidentiality;
- demand in the affected areas – information regarding the demand in the affected areas, either aggregated or on the substation-by-substation level; data here included the maximal power of the demand, daily variation profile, share of different load types (household, industry, EVs) and estimation of the capability of this demand to provide flexibility to the system if needed;
- technical data on the MV lines in these areas, provided in the defined tabular form.

Of course, in addition to all of these, both TSO and DSO, as well as the remaining partners, had a vital role in following the regulatory framework in Bulgaria and paying attention to avoiding the simulations of the processes and actions that would (partially or completely) go against the relevant regulations.

5.3 Datasets Requested from the TSO

The largest part of the conducted data collection referred to the information that was requested from the partners that represent Bulgarian TSO. This part of the report will give some insight into the exact datasets that were necessary (of course, if available and not marked as confidential) for each of the selected four points of interest in the Bulgarian transmission grid (all of these were explained before).

5.3.1 Technical Data

The first section of this subchapter will focus on the technical characteristics of the separate elements of the system, as well as the model of transmission system as a whole. It will therefore be divided into individual parts for production units, overhead lines, and simulation models of interest for the project.

The tables in this subchapter, related to the technical system data, are empty since they are only the illustrations of the datasets provided by the TSO. It was not possible to show the exact values given by the TSO here, since that information is private and belongs to the respective owners. Giving them here would mean a breach in data confidentiality, but templates do give insight into what was used.

5.3.1.1 Production Units' Technical Data

This part of the text will focus on the technical information on the production units connected to the transmission grid. The first given table shows the spreadsheet that had to be filled in for wind turbines in the selected WPP. Here, *n* indicates that number of columns is equal to the number of turbines.

Table 5-2 – Wind turbine technical data table

Parameter / information	Turbine 1	Turbine 2	Turbine 3	Turbine *n*
Turbine type				
Longitude				
Latitude				
Altitude				
Rotor diameter				
Tower height				
Rotor height				
A-factor				
Form factor, *c*				
Annual average wind speed				
Vertical average shear component				
Extreme wind speed (10 min average)				
Survival wind speed (3 sec average)				
Automatic stop limit (10 min average)				
Rated power				

Rotor speed				
Rated wind speed (30 sec average)				
Cut-in wind speed (3 sec average)				
Cut-out wind speed (10 min average)				
Restart wind speed (10 min average)				

In addition to the technical information listed in Table 5-2, the TSO was also asked to provide production curves for the different types of turbines in this WPP, with the example of this curve, indicating the production power of the turbine depending on the wind speed in the chosen location, provided in the figure below (the figure is purely illustrative and doesn't correspond to any unit found in the Bulgarian grid or plants connected to this grid). It can be seen that the boundaries for the operation of this wind turbine are 3 m/s as cut-in speed and 25 m/s as cut-out speed, with about 2.1 MW of rated power.

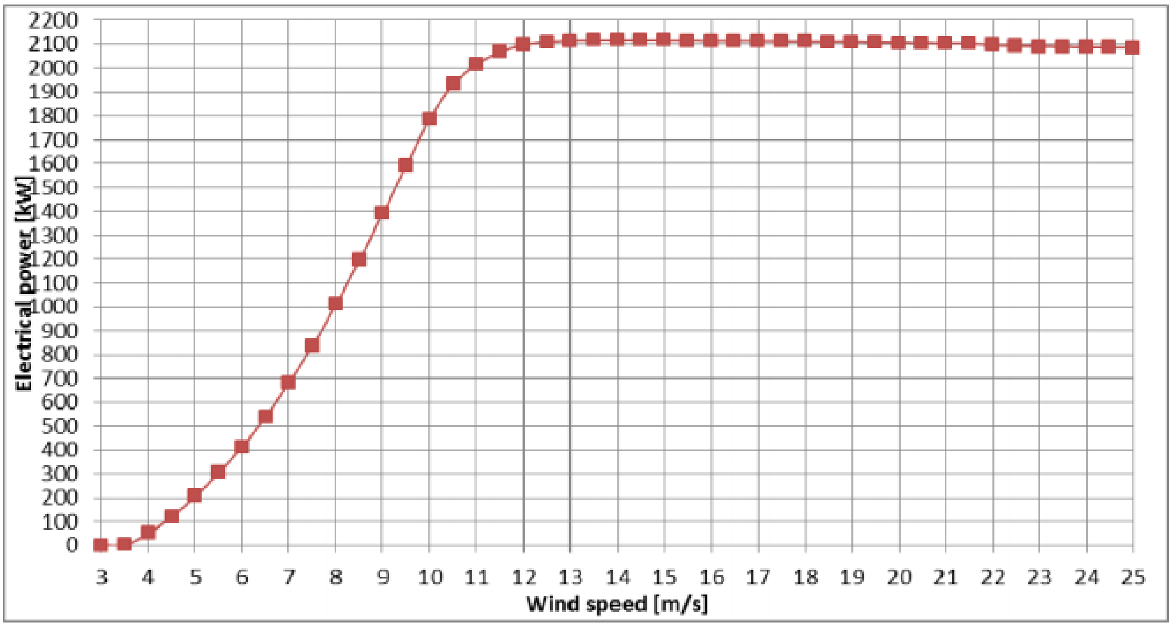


Figure 5-6 – Example of the wind turbine production power curve

Continuing where the data required for the wind units left off, there was also a list of information that needed to be collected for the solar units in the selected solar power plant. This list can be found in the table below, focusing both on the location of each section of photovoltaic (PV) panels and on their characteristics such as the tilt angle and the conversion factor. All of these were needed for the proper understanding of the other provided data and running the forecasts for SPP Karadzholovo. Again, *n* in the last column shows that the number of columns corresponds to the number of PV panels' sections.

Table 5-3 – Solar unit technical data table

Parameter / information	Solar unit 1	Solar unit 2	Solar unit 3	Solar unit *n*
Longitude				
Latitude				

Altitude				
Conversion factor				
Tracking or static panels				
Panel´s tilt angle				

5.3.1.2 Overhead Lines' Technical Data

Aside from the technical data that needed to be collected for the production units operational in the regions of interest, similar kind of information also had to be collected for the selected overhead lines as well. For these lines, focus has been put on the accurate information regarding each tower on their routes. This information, as shown in the table below, included data on latitude and longitude of each tower, their height, as well as the altitude at which they are located. All this proved to be vital for the forecasts of the ampacities of these lines. Tables similar to the one provided below needed to be filled in for each of the two selected transmission lines (one 400 kV and one 220 kV) in the Bulgarian grid.

Table 5-4 – OHL technical data table

Parameter / information	Tower 1	Tower 2	Tower 3	Tower *n*
Longitude				
Latitude				
Altitude				
Tower type				
Tower height				

5.3.1.3 Grid Models for Selected Operational Regimes

Finally, last set of purely technical data referred to snapshot network models of the grid (voltage levels equal to or above 110 kV). These snapshots both served as foundation for EHV-HV DT and gave insight into the topology of the grid in different conditions under which the grid may operate throughout the year. In line with this, for years 2018, 2021, 2023 and 2024, the following regimes were requested:

- Summer off-peak hour;
- Summer peak hour;
- Winter peak hour;
- Max solar production hour;
- Max wind production hour;
- Max solar + wind production hour;
- Min wind production hour;
- Morning minimum with a sudden wind;
- Day with the incoming cloudiness (few hours to be analysed);
- Hours with the poor wind and solar production forecasts;
- Max net import of Bulgarian control area hour;

- Max net export of Bulgarian control area hour;
- Hours with max flows on each of selected lines (two snapshots per year);
- Hours with forced unplanned outages (generation units or major OHLs);
- Any other TSO-specific regime.

It should be underlined that final bullet point referred to any regime that TSO deemed important, and it was not specifically mentioned before. In order to be fully compliant with the provisions of the DTs that were expected to be made, the snapshot models had to be delivered in appropriate PSS/E format.

5.3.2 Weather Data

The next set of data that was connected for the Bulgarian grid (with the special focus on the chosen areas) referred to the relevant climatic parameters. Information was collected on the hourly level, covering previous decade (i.e. period from 2015 to 2024). In addition, data covered all four selected locations of interest for the project, with data for wind and solar park covering smaller scope than the datasets for routes of entire overhead lines. The information that had to be collected can be found in the list:

- Pressure/Wind speed 10m;
- Pressure/Wind speed 100m;
- Pressure/Wind;
- Clouds;
- Convective clouds;
- Low clouds;
- Rain;
- Temperature;
- Soil temperature;
- 500 hPa temperature;
- 700 hPa temperature;
- 850 mb temperature;
- Visibility;
- Soil wetness;
- Snow;
- Snow depth;
- Rain/Snow;
- Daily precipitation (acc);
- Daily snow (acc);
- 500 hPa wind;
- Solar radiation.

It is clear that the list given here was rather extensive, but it has to be underlined that only the highest possible quality and resolution of the information provided by the TSO could enable foreseen work on the forecasts and application of the ANN-based tool to make sense. For example, forecasts of the wind units' production needed accurate information on the georeferenced locations of every wind turbine and the conditions which were valid at that location at the selected hour (wind speed, wind direction, temperature, etc.). By pairing those climate conditions with corresponding production power for the sufficient number of hours, ANN was given the possibility to spot the correlation between all of these factors. When that happened, ANN model was trained and could then be used for the future forecasts of the production powers of the WPP, utilizing the known weather factors to highest possible extent. Same goes for solar panels, with the list of necessary information varying just slightly compared to the (e.g., for the wind turbines, wind speed and direction were crucial, whereas, for the solar units, focus shifted to the clouds and to the irradiation in the observed hours). In addition to this, forecasts of the OHL ampacity brought in additional level of complexity, as the ampacity of the line generally depends on the value of ampacity in the most critical span. This principle is what is typically known as weakest link approach, and it also had to be accounted for in the forecasts that were performed in this pilot.

5.3.3 Energy Data

The final set of information that was requested from the Bulgarian TSO was the one referring to the energy flows data and the inputs needed for the estimation of the actual loading of lines of interest for pilot.

5.3.3.1 Historical Energy Flow Data

This part of the data collection referred to the historical hourly flow data for period from 2018 to 2024, with the focus primarily being (but not limited to) the information that is provided in the list below:

- Hourly power flows (P [MW], Q [MVAr], with a clear indication of the flow direction) on both the interconnection line of interest for Bulgarian pilot (OHL 400 kV SS Blagoevgrad – SS Thessaloniki) and the selected internal line in the transmission grid (OHL 220 kV SS Plovdiv – SS Aleko);
- Hourly data for WPP Sveti Nikola, which had to include (at least) aggregated hourly information on the production power for the 2018-to-2024 period [MW], as well as the outside temperature [˚C], solar radiation [W/m²], and wind speed [m/s] at this wind power plant's location;
- Hourly data for SPP Karadzholovo, which had to include (at least) aggregated hourly information on the production power for the 2018-to-2024 period [MW], as well as the outside temperature [˚C], solar radiation [W/m²], and wind speed [m/s] at this solar power plant's location.

The listed datasets, together with the remainder of the information explained in the previous sections of the Chapter 4, served as the foundation for the establishment of the relations between the values of the flows and productions on one side and the relevant set of the climate conditions on the other side. Of course, the same procedure would work if the data received was given with 15-minute resolution, with the accuracy of created ANNs probably getting even higher due to more information available.

5.3.3.2 Cross-border Market Data

The next contribution that has been required from the Bulgarian TSO referred to the simulation model of the cross-border energy market, which also served as a basis for the DT covering this topic. This model provided the required hourly values of the inputs needed for the EHV-HV and MV DTs, with the flow of this process roughly corresponding to the three main steps that are provided in the list below:

- The first step of the procedure included combination of the relevant climate parameters with the ANN-trained auxiliary DTs of the generation units and the power plants in order to obtain hourly data regarding the production powers of the selected wind and solar park in the Bulgarian grid;
- The second step of this process involved the update of cross-border market DT by implementing the obtained forecasts of the production powers of the selected units, after which the simulation was run in order to find out exchanges between Bulgarian system and the neighbouring systems;
- Final step that was done here enveloped the communication between the market and network DTs in order to utilize outcomes of the market simulations as the inputs for the network analyses, in line with the descriptions of Use Cases that needed to be considered within the Bulgarian pilot.

In line with the needs of the pilot and the DTs that was developed, the required model had to be given in the form compatible with the direct import into the ANTARES software tool. This ensured maximum efficiency by avoiding delays that would otherwise occur due to the need for inter-format conversion.

5.3.3.3 Grid Connection Data

Finally, it was stated in the previous parts of this report that the BUC 06 had to deal with optimization of connections of new units in the grid (with these units being either the renewable energy sources or the energy storage systems). For that to be possible, the list of connection requests that are publicly available and can be used in pilot activities was required from the Bulgarian TSO, with fall-back options such as data anonymization or aggregation and using virtual facilities instead of real-life connection requests envisaged in case the exact data couldn't be provided due to confidentiality-related issues.

5.3.4 Data Collection Outcomes

In line with what was expected during the preparations of the data delivery templates and hinted at in the previous paragraph of this report, the only actual issue that happened during the data collection process was the problem of Bulgarian TSO not being able to provide the confidential information that is related to the requests for the connection of new production and storage units. After some internal discussions, it was concluded that the anonymization of data still wouldn't do enough for this data to be used and published in the scope of TwinEU activities. Thus, it was decided to use the virtual facilities for the needs of the BUC 06, avoiding any kind of sensitive information that would otherwise need to be disclosed. It was also stated at that time that this does not harm the outcomes and achievements of the project to any extent, since the point of this Use Case was not to give the manners of connecting the facilities that would later on be used by the TSO and communicated with the clients. Rather, the main goal was to showcase the way in which the selected optimization technique can be used for the purpose of choosing the connection points, which could be done just as fine with the virtual facilities.

5.4 Utilizing Datasets for ANN-based DTs

In the Subchapter 3.5, it was emphasized that, in order to properly develop the ANNs for forecasting purposes, it is necessary to pick the relevant set of input data and then to split that data in the subsets that will cover the training, validation, and testing of the ANN. For the forecasting purposes relevant in the scope of the Bulgarian pilot, input data consisted of the recorded values of the chosen technical parameters (for example, if the forecasts are done for the wind unit production, they take into account the production powers in the hours preceding the forecasting period). Regarding the climate data, the following set has proven to be of the utmost importance for the desired accuracy level to be reached:

- wind speed and direction;
- air temperature;
- solar radiation (SWR);
- total clearness (TOTCL);
- relative humidity (RH).

Additional features such as season and time of day were also considered in order to properly capture the diurnal and seasonal patterns commonly occurring in the variation of selected indicators' values. Once the identification of the relevant inputs was finished, it was possible to move on to the division of the available datasets into three subsets, with the ratios of these subsets' sizes selected to ensure maximal efficiency and precision of the forecasting process. Hence, 70% of the available data was used to train the forecasting ANNs, 15% was utilized in the validation procedure, whereas the final 15% was applied for the testing of those ANNs. The results that were obtained by using these ANNs are going to be presented in the upcoming chapter of this report, split by the BUCs for which they were relevant.

6 Discussions of Results

As mentioned in one of the previous sections of this deliverable, the manner in which the results and achievements of the pilot will be presented will correspond to the way in which the work conducted in it was organized – on the UC level. Hence, each of the subchapters in this chapter will be dedicated to one of the UCs explained in Chapter 4, starting from the ten BUCs and then moving on to the four SUCs defined in the pilot. After the presentations of the results related to each of the UCs, evaluation on whether the KPIs (Key Performance Indicators) assigned to it were reached in this project or not.

6.1 BUC 01 - Results

The first BUC of the Bulgarian pilot, in line with how it was defined and described, focused on drafting the codes necessary for the information exchange between the DTs, with the particular attention on bridging the gap in communication between the three utilized software tools – PSS/E, ANTARES, and Microsoft Excel. Therefore, this BUC represented a precondition for any other work in the pilot, so the results of all other UCs could not be obtained without its proper completion. Regarding the outcomes of this BUC, those can be split into two main codes that were written, tested, and finally applied in the scope of pilot's activities. The first of those was the one focusing on data exchange between ANTARES model and Microsoft Excel (in particular, the goal here was to export the results of round-year market simulations into the made-for-purpose Excel spreadsheet). The second drafted code was dedicated to data exchange between that Microsoft Excel and PSS/E (by implementing the outcomes of the market calculations into the grid model). The former was hence written in R programming language due to its compatibility with ANTARES, while Python was used to write the latter as it is compatible with PSS/E.

```
#get wind generation
wind_2030=subset(area_data_all_2030$areas, area==i)$"WIND ONSHORE"

if(length(wind_2030)==0) {
  wind_2030=replicate(8736,0)
}

#get solar generation
solar_2030=subset(area_data_all_2030$areas, area==i)$"SOLAR PV"

if(length(solar_2030)==0) {
  solar_2030=replicate(8736,0)
}
```

Figure 6-1 – R code – reading wind and solar productions

The first main code was divided into the two logical segments – the first half of it was written to read the results directly from ANTARES tool, and the second half of it was intended to write those results into the Microsoft Excel spreadsheet of user's choice. It should be underlined that it was assumed that there is no need to automatically run the ANTARES simulation or to adjust the time series in ANTARES according to ANN-based forecasts, as this would be done beforehand by the relevant system operator. The "reading" part of the code was split into parts, with each of them covering the reading of one of the result types – exchanges between the Bulgarian system and the systems around it, productions of different generator categories (aggregated or on the unit-by-unit level), storage activation mode and power, etc. The example of this code part can be seen in Figure 6-1, in which the lines defining reading of the wind plant productions and solar plant productions (aggregated on the system level) are given.

It should be mentioned here that the fact ANTARES treats only the thermal generation fleet on a unit-to-unit basis, whereas all other types of generation get aggregated posed a particular challenge during the input of obtained results in the PSS/E model (in which all generation types are treated on the unit level). However, this was resolved by adding specific lines into the Python code that will be described a bit later on. The second part of the code in R focused on writing the read results into the predefined Excel file, with general data regarding the BG00 (code for the Bulgarian area in the ANTARES market model) added first, followed by the part of the code dealing with the writing of the energy exchanges between the Bulgarian system and the surrounding systems (here, GR00 stood for Greece, MK00 was the code for North Macedonia, RO00 stood for Romania, RS00 was for Serbia, and TR00 was the code for Turkey). The lines of this code covering the addition of the cross-border exchanges into the Excel spreadsheet, after which that Excel file is saved, are given as an illustrative example in the Figure 6-2.

```
#Exchanges

bg_gr=t(t(subset(links_data, link=="bg00 - gr00")$"FLOW LIN."))
bg_mk=t(t(subset(links_data, link=="bg00 - mk00")$"FLOW LIN."))
bg_ro=t(t(subset(links_data, link=="bg00 - ro00")$"FLOW LIN."))
bg_rs=t(t(subset(links_data, link=="bg00 - rs00")$"FLOW LIN."))
bg_tr=t(t(subset(links_data, link=="bg00 - tr00")$"FLOW LIN."))


#add exchanges in excel
writeData(wb,bg_gr,sheet = "Crossborder exchanges",startRow = 12,startCol = 3,colNames = FALSE)
writeData(wb,bg_mk,sheet = "Crossborder exchanges",startRow = 12,startCol = 4,colNames = FALSE)
writeData(wb,bg_ro,sheet = "Crossborder exchanges",startRow = 12,startCol = 5,colNames = FALSE)
writeData(wb,bg_rs,sheet = "Crossborder exchanges",startRow = 12,startCol = 6,colNames = FALSE)
writeData(wb,bg_tr,sheet = "Crossborder exchanges",startRow = 12,startCol = 7,colNames = FALSE)

saveWorkbook(wb, paste(path_results,"Export results from market model_BG.xlsx"))
```

Figure 6-2 – R code – writing energy exchanges in Excel file

```
# Excel 1

df_hourly = pd.read_excel(excel1_path, sheet_name='hourly_agregated', header=1)
df_types = df_hourly.iloc[:, 1:12]        # columns B:L → productions by unit types
df_total_load = df_hourly.iloc[:, 12]     # columns M → total demand

df_crossborder = pd.read_excel(excel1_path, sheet_name='Crossborder exchanges', header=0)
df_crossborder_areas = df_crossborder.iloc[:, 1:6]  # columns B:F → neighboring areas
```

Figure 6-3 – Python code – reading the ANTARES results

It can be seen that, once the R script finishes its operation, it creates an Excel file containing all of the input data necessary for creating the EHV-HV DTs. These values are given at an hourly level. Next part of the automation process was to create a python script that would read those results and, based on them, create predefined number of hourly PSS/E models in which the ANN-made forecasts would be implemented. As the ANN-based forecasts could look 72 hours in advance, this Python script needed to be capable of making 72 PSS/E models, one for every hour enveloped by the forecasting period. In order to do so, this script first had to read two Excel files – one file containing the outputs of ANTARES cross-border energy exchange DT and the other file with the exact values of the forecasts of selected parameters (here, those were WPP Sveti Nikola and SPP Karadzholovo production powers, as well as the ampacities of the two selected lines). The example of the part of the code that deals with reading the hourly results of the ANTARES calculations can be seen in Figure 6-3. These lines of the code read the exact same format of the Excel spreadsheet as the one that was previously created by the R script.

Once the results and forecasts are successfully read, python script moves on to the second part of the process, in which 72 PSS/E models have to be created. To do so, the script opens the base model (the only condition for this model is that it has to have the grid topology valid for all three days for which the forecasts are valid) and then updates the parameters in it to adjust it to the forecasts and ANTARES results. There the particular attention had to be given to splitting the total WPP and SPP productions (as those are extracted from ANTARES aggregated on the area level) into the productions of separate units, all while respecting the forecasts of relevant indicators. Once the parameters in the grid model get adjusted to the target values, the model is saved with the indicator of the hour to which it refers, after which the process is repeated all the way until the model for the final hour gets created. Some of the lines included in this part of the code can be seen in Figure 6-4. These lines are, for example, in charge of saving the developed model and verifying whether or not the saving process was successful.

```
# Save hourly model
sav_output = os.path.join(output_folder, f"model_hour_{hour_idx+1}.sav")
ierr = psspy.save(sav_output)
if ierr == 0:
    print(f"✅ Model saved: {sav_output}")
else:
    print(f"⚠ Error in saving")
```

Figure 6-4 – Python code – saving the hourly model

Once the models for every hour are made 72 hours in advance, the user (which would, in this case, be the system operator) could do all of the necessary calculations and analyses on these models, making sure to have the accurate vision of the system state within the three-day horizon. This can ensure that the issues in the grid get spotted in a timely manner, giving the respective operators time to plan their actions appropriately and to mitigate consequences that could occur if no activities were commenced.

Regarding the measure of the success of this BUC, two KPIs have been specified in BUC definition step. These KPIs are provided in Table 6-1, along with some of the basic descriptions and parameters that are related to them, such as target values that were supposed to be reached for BUC to be successful.

Table 6-1 – KPI definition – BUC 01

KPI number	KPI name	Target value
BG-BUC01.01	Percentage of verified DTs [%]	100%
BG-BUC01.02	DT interoperability success rate [%]	100%

The first of these two KPIs was based on comparing the number of major DTs verified by the respective SOs and the number of total major DTs created in the scope of the pilot. There were three total major DTs created in the scope of the pilot at the time of this report’s drafting. All of them were also verified by the SOs (two by the TSO and one by the DSO), meaning that this KPI has reached its target value of 100%. The second KPI here measured the success and accuracy of the data exchange between the DTs by using the developed codes, which as measured by taking values from ANTARES tool and comparing them to the values of those same parameters that were implemented in the PSS/E models by scripts. As there was a match between all selected pairs of values, it was concluded that this KPI also managed to reach its defined 100% target value. Thus, the BUC 01 could have officially been declared a success.

6.2 BUC 02 - Results

This BUC deals with the utilization of trained-for-purpose ANNs for achieving minimal prediction errors in the WPP power forecast. The accuracy of these forecasts strongly depends on the quality and organization of the input database. Well-structured, accurate, and comprehensive input data directly improves the performance of ANNs. For wind power plants, meteorological parameters are of utmost importance. To be exact, for wind power plants, these meteorological parameters were wind speed and wind direction. These inputs for the WPP-forecasting ANN are provided in Figure 6-5. Further improvement of the results was obtained by adding lag features into the ANN code. Here, lag features were production from the same hour on the previous day and production from previous hour.

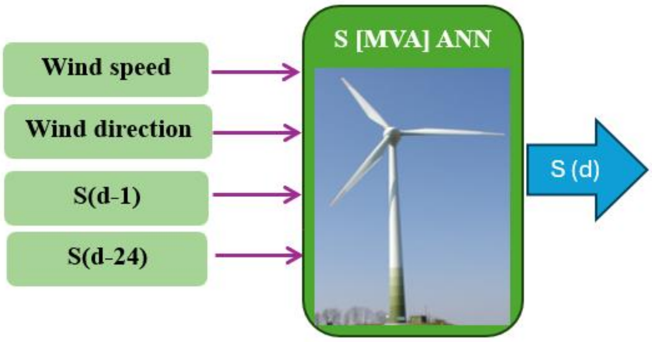


Figure 6-5 – Schematic of ANN DT model of WPP

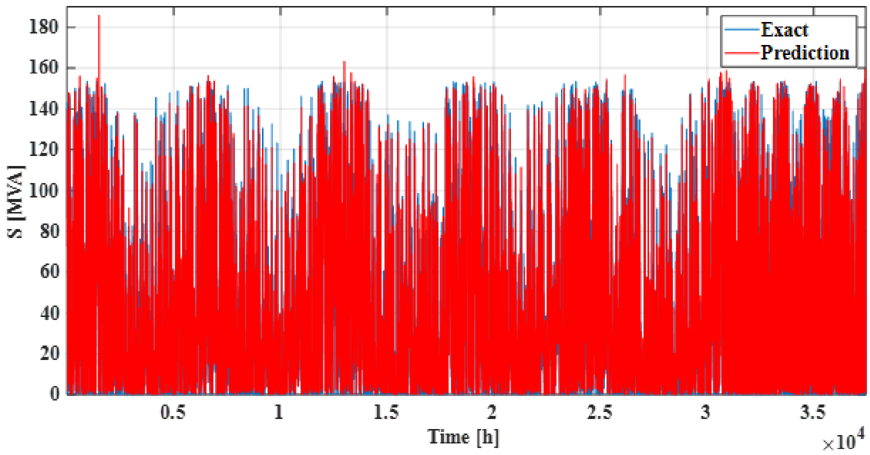


Figure 6-6 – WPP power prediction for training dataset

The dataset that was applied for WPP-forecasting ANN covered the period from the beginning of 2018 all the way up to the end of 2024, containing over 60000 hourly records. For WPP Sveti Nikola, optimal ANN configuration was the one with 2 layers of [64, 32] neurons. This configuration was determined by trial-and-error process, where different potential structures of the ANN were tested, with the ones with the better results getting refined further until the best one was determined. The same procedure was applied for sizing other developed ANNs as well. By using this configuration, MAPE level of 5.09% was achieved. Figure 6-6 shows ANN prediction results over a test-set of over 35000 production values for this WPP. A good match between the blue line (measured values) and red line (forecasted values) can be seen here, with the main trends in production behaviour getting mimicked by ANN perfectly.

However, the sheer amount of data shown in the previous diagram could potentially make it difficult for the reader to properly notice the mentioned match between the trends that were spotted in the measured data and the tendencies demonstrated by the ANN-based forecasts. In order to emphasize the accuracy of the forecasts and make it easier to see, additional diagram was also constructed, with the focus being on one random week within the training period. That diagram is shown in Figure 6-7.

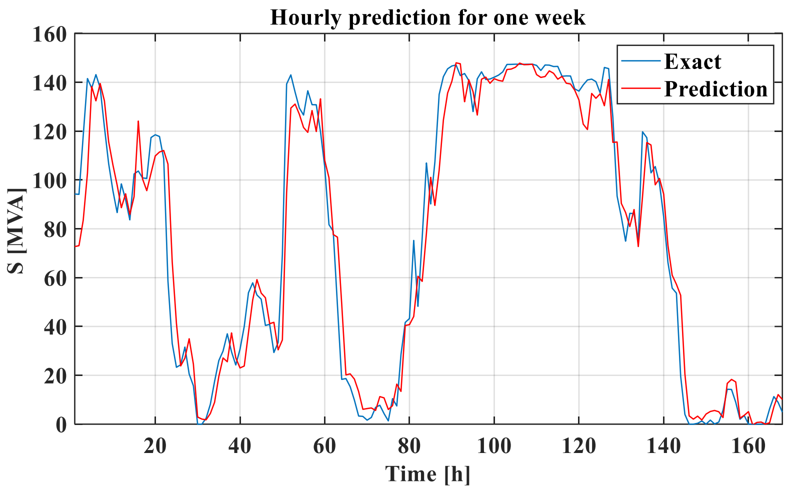


Figure 6-7 – WPP power prediction for one-week period

In accordance with what was already presumed, this kind of illustration highlights the precision of the performed forecasts in a much clearer and more comprehensive way, since it actually allows for hour-by-hour parallel analyses of measured generation powers and forecasted generation powers in same hours. If one would do this, they could see not only that the trends in the measured data are properly followed by the forecasts, but that the ANN-given values actually match the values of the productions almost perfectly in most hours. This accounts for the near-to-5% MAPE value enclosed on the previous page. Along with being a general indicator of the forecasting procedure's success, this MAPE value is also relevant to the success for the BUC 02 of the Bulgarian pilot, since the KPI that has been defined for this UC is directly related to its comparison with the standard errors that are made during the WPP generation predictions. This KPI can, along with accompanying reference value, be seen in Table 6-2.

Table 6-2 – KPI definition – BUC 02

KPI number	KPI name	Target value
BG-BUC02.01	Improvement of WPP forecast accuracy [%]	> 1%

The only question that could be raised here was which error could be taken as the standard reference error to which the MAPE value obtained through the forecasts would be compared. For the reference value (as agreed with the Bulgarian TSO), the standard values from literature were taken, with these values going from 7% to 10%, with 9% being the commonly assumed value. The value also shows the tendency to grow when going from day-ahead forecasts to three-days-ahead forecasts, with the latter being relevant for the Bulgarian pilot. Since the MAPE value obtained in the pilot just slightly exceeds 5%, it is obvious that the improvement made when compared to the reference value is indeed greater than 1%. As this was the threshold value set for this BUC and the forecasts performed in it, this was taken as the signal to mark the conducted forecasts as accurate and the BUC 02 of pilot as successful.

6.3 BUC 03 - Results

Continuing where the previous BUC left off, BUC 03 was, as it was thoroughly described in Subchapter 4.3, the one that also dealt with applying the ANN that was made especially for this purpose in process of forecasting the production powers of SPP in the Bulgarian system. Aside from the fact that the type of the unit for which the forecasting has been done was different, this BUC had a lot of similarities to the one preceding it, especially in terms of the adopted assumptions and conditions which needed to be met in order for the forecasts to be done properly. According to this, the quality of the input data had to be of the highest level once again, since even the slightest issues with the accuracy of this data could harm the training procedure of the ANN. For the meteorological data relevant for this case, wind speed, solar radiation, and temperature proved to be of relevance. Along with these, the day and night cycles were also vital to be accounted for, and inclusion of the lag features again managed to improve the forecasts' reliability by a great scale. Inputs for the SPP-forecasting ANN are given in Figure 6-8.

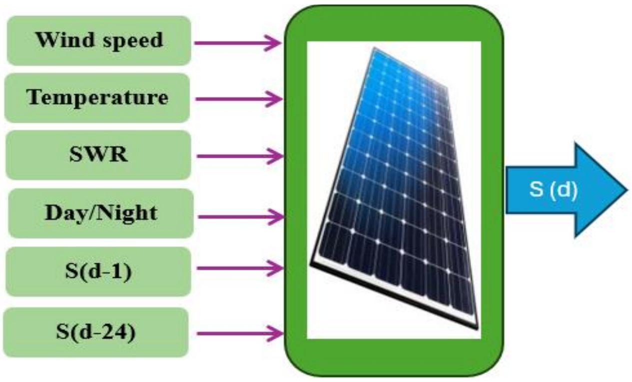


Figure 6-8 – Schematic of ANN DT model of SPP

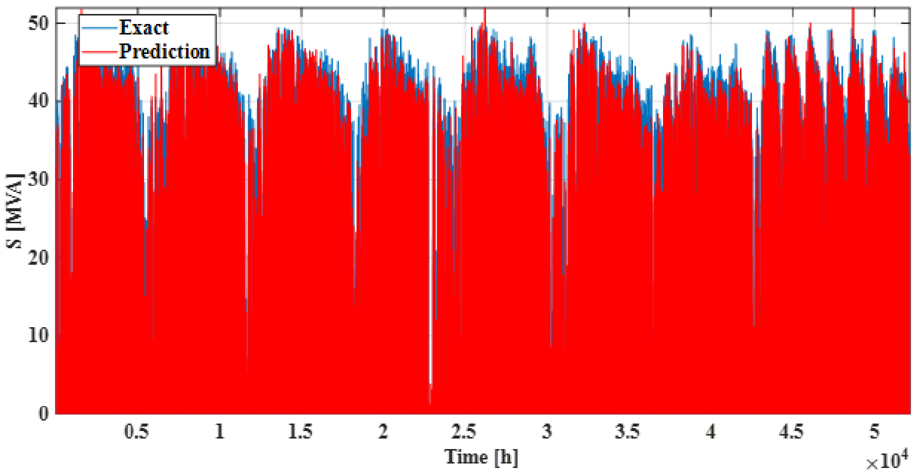


Figure 6-9 – SPP power prediction for training dataset

The available dataset once again included over 60000 hourly records (or seven whole years). Optimal configuration that was achieved for SPP Karadzholovo consisted of 3 layers with [64, 32, 24] neurons. By applying ANN that was adjusted in line with this description, MAPE level of 3.08% was reached. The Figure 6-9 provides an insight in the ANN-based prediction results over a test-set of more than 50000 production powers for this solar park. Good match can once again be seen between the shown values.

Even more than in the case of WPPs, the full scale of the training data shown in a single diagram gives little information aside from the fact that trends of growth and fall of the forecasts follow tendencies of the production powers collected from the TSO. However, in order to properly demonstrate this, it was once again better to select a random one-week period from the training set of data and illustrate how the forecasts follow the production powers almost perfectly. This diagram is given in Figure 6-10.

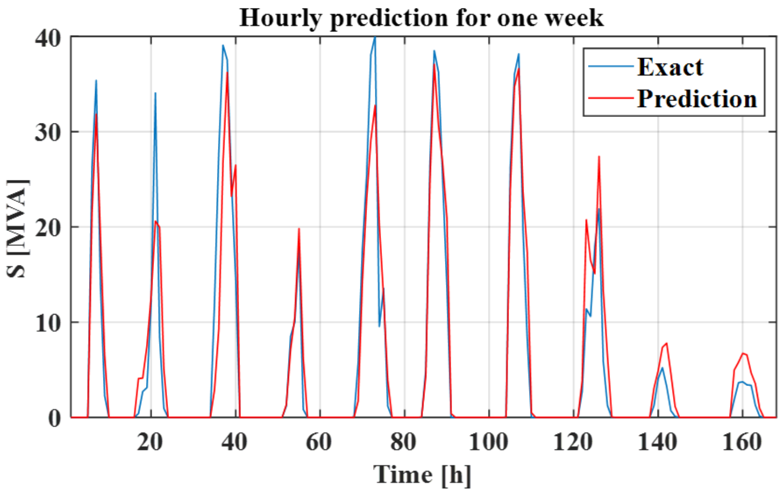


Figure 6-10 – SPP power prediction for one-week period

This diagram gives possibly an even better insight than the similar one that has been created for the WPP production forecasts. The reason for this can be found in the simple fact that the SPP production is cyclical and behaves in accordance with the changes of day and night. Hence, it's much easier to see if the forecasts fall down to zero (or near-zero) value at the same time as the measured values than if the forecasts (as is the case for the WPPs) follow the change of the few percent in generation powers. The obvious match also illustrates the remarkably low MAPE value of close to 3% obtained for this UC and mentioned in the previous page. Once again, this MAPE value is not only important to accentuate the accuracy of the forecasts, but it is also necessary to check if the defined KPI for this BUC has been reached, as it directly depends precisely on the MAPE value. This KPI can, along with the target value of it that was used as a threshold for the success of the BUC, be seen in the Table 6-3, enclosed below. Since this BUC is almost the same as the BUC 02, it was only logical to also use similar KPIs for them.

Table 6-3 – KPI definition – BUC 03

KPI number	KPI name	Target value
BG-BUC03.01	Improvement of SPP forecast accuracy [%]	> 1%

In the same fashion as in the BUC 02, here the question could also be raised of the reference that can be used for the comparison with the obtained MAPE to check if the achieved improvement was indeed greater than 1%, meaning that, if so, the BUC was successful. For this reference, in line with what was discussed with the partners from Bulgarian TSO, the value of 5% was adopted. If one now compares this reference value with the MAPE calculated based on the forecasts, they could easily conclude that improvement of SPP productions forecasting accuracy that was achieved was almost double the value that was picked as an indicator of the properly completed BUC. In line with this, it was safe to say that the forecasts were indeed improved by ANN application and that BUC 03 was successfully completed.

6.4 BUC 04 - Results

The third ANN that was supposed to be developed in the scope of the Bulgarian pilot was the one that focused on forecasting the ampacities of the overhead lines in the grid based on the defined climatic conditions along their routes. However, there was, first of all, an issue regarding the available dataset. Namely, the goal of the ANN was to be able to provide forecasts of the line ampacities for the chosen number of hours in advance. For this, ANN needed to have two sets of inputs at disposal. The first one was the set of needed climatic parameters. This was not an issue, since the similar set of data was also utilized in order to complete BUCs 02 and 03 successfully. The second part of the inputs was, however, an issue. This set had to focus on the actual ampacities of the lines that corresponded to the climatic parameters from the first part of inputs, since having this available was the key for the ANN to be able to establish correlations between the ampacities and the climatic parameters, leading to the forecasts of those ampacities becoming possible as well. Since the Bulgarian TSO commonly uses only the static ratings of the lines, the required kind of information was not at the immediate disposal of the partners from that company. Thus, this input set needed to be created before the development of ANN began.

In order to do this, it was first necessary to understand how the ampacity of the line can be calculated and what kind of input data were essential. For that, IEEE 738-2023 IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors had been consulted. The calculation of ampacity of the overhead line, based on the standard, starts by understanding thermal equation of the overhead line, i.e. what are the factors that increase the conductor temperature and what are the factors that decrease it. In this standard, two factors are listed as the ones that heat the conductor up and other two are given as the ones that cool it down. These factors are illustrated in the figure below.

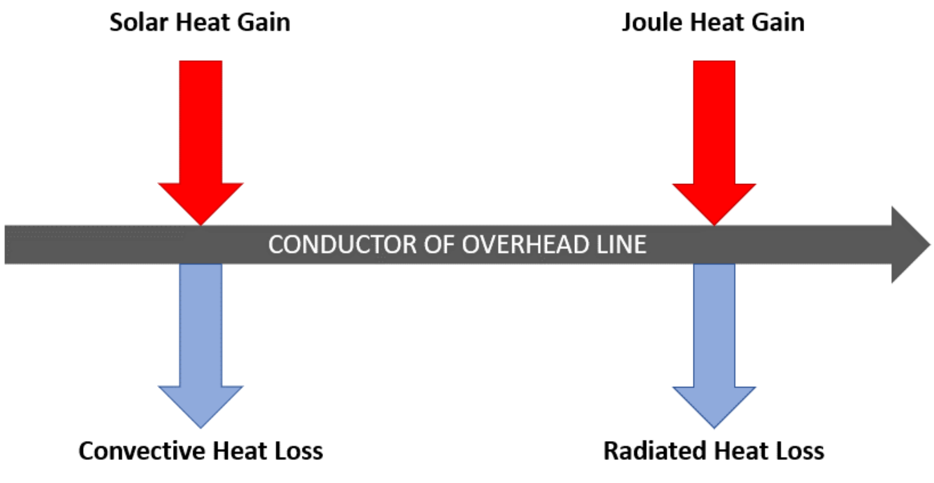


Figure 6-11 – OHL heat impacting factors

The difference between heat gains and losses, illustrated in the Figure 6-11, is directly proportional to the thermal gradient of the line (or, simply put, the speed by which the temperature of the conductor changes). If the heat gain is higher than the heat loss, the temperature gradient will be positive, and vice versa. This can also be seen in appropriate Formula (6.1), where ϑ marks the line's temperature.

$$\frac{d\theta}{dt} = \frac{1}{m \cdot C_p} \cdot (q_J + q_S - q_C - q_R) \tag{6.1}$$

Regarding the symbols other than the temperature itself, *m* in this equation marks the conductor mass per unit length (dependant mostly on the type of conductor and the materials used to make it), while C_p marks the mean specific heat capacity of the conductor. Along with those, q_J stands for Joule heat gain, q_S for the heat gain coming from the solar radiation, q_C for the convective heat loss, whereas q_R marks the radiated heat loss, as shown in the Figure 6-11. Now, the way the ampacity of the conductor can be extracted from the upper formula starts from the assumption that this ampacity is actually the value of the current through the line for which the heat balance of the line is achieved on the maximal permanently permitted temperature of that line. For the heat balance to be achieved at all, gradient of temperature change needs to be equal to zero. That means that terms in the bracket need to cancel each other out, i.e. that the total heat gain of the line has to be equal to the total heat loss of the line. From there, the necessary value of Joule heating (depending on the current) can easily be extracted, as shown in Formula (6.2). In this, ϑ_{max} marks the maximal permanent temperature of the conductor.

$$q_J(\theta_{max}) = q_R + q_C - q_S \tag{6.2}$$

Now, it is stated that this is Joule heating at the maximal permitted temperature of the line since the value of Joule losses depends on two parameters – one of them is the squared value of current through the line, and the other is resistance of the line. The resistance is what changes with temperature. Thus, the resistance (*R*) that corresponds to the maximal line temperature has to be considered when one calculates the ampacity of the line. This approach is also illustrated in Formula (6.3), enclosed below.

$$q_J(\theta_{max}) = R(\theta_{max}) \cdot I^2 \tag{6.3}$$

By changing q_J in the Formula (6.2) by its form given in Formula (6.3), one can easily calculate the value of the current for which the heat balance of the line is reached at the exact temperature that has been defined as the maximal allowed temperature of the line. The manner in which this can be performed is shown in Formula (6.4), where *Imax* stands for this value of the current, i.e. the ampacity of the line.

$$I_{max} = \sqrt{\frac{q_R + q_C - q_S}{R(\theta_{max})}} \tag{6.4}$$

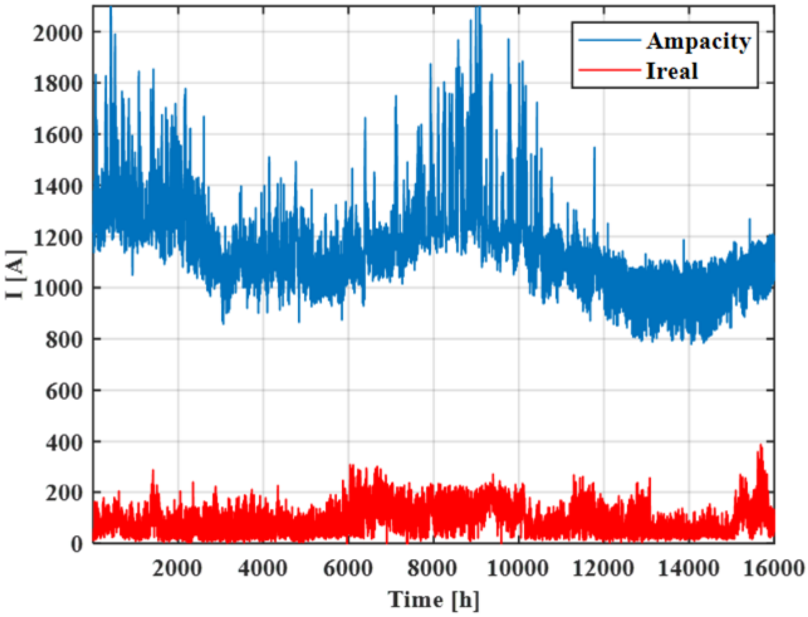


Figure 6-12 – Calculated ampacities – internal line (entire period)

It is worth noticing here that the remainder of the parameters included in the Formula (6.4), such as the different heat gains and losses of the line that need to be accounted for, depend on the technical characteristics of the conductor, but also on the climate conditions which are valid along the route of the observed line. For instance, convective heat loss is mostly dependent on the wind speed and wind direction (i.e. the angle between the line route and the direction of the wind, since it affects the way in which the wind cools the conductor down). In addition to that, radiative heat loss depends mostly on the difference between the line temperature and the outside temperature along the route, while the solar heating depends almost entirely on the solar radiation. Even though this might appear like a lot of information, it was actually successfully delivered by the Bulgarian TSO for the lines of interest. The application of Formula (6.4) for every hour in the observed period gave a possibility to determine the ampacities of the lines for those hours. As BUC 04 of the pilot concentrates on the internal line, in Figure 6-12 one can find the calculated ampacities of the 220 kV OHL SS Plovdiv – SS Aleko (blue line), whereas the red line (for comparison) illustrates the actual currents on that line for the same period.

For this, the maximal conductor temperature of 80 ˚C was chosen, as this is the common temperature at which the safety parameters of the line's operation may be put at risk. This was the dataset which was used to train the ANN for the ampacity forecast of the internal line in the Bulgarian transmission system. The ANN's optimal configuration this time consisted of 3 layers of [24, 12, 24] neurons. When this configuration was applied, the MAPE value that was obtained by comparing the ANN-determined ampacities and the calculated ones for the same period was equal to 0.05%. This error is much smaller than the one spotted for the WPPs and the SPPs, but this only has to do with the fact that the relation between the relevant parameters and the ampacity is much more straightforward (and illustrated by the formulae above) than it is the case with the production powers of the variable renewable sources. In order for this accuracy to be illustrated, Figure 6-13 has been made, showing the perfect match of the ANN-forecasted values and the calculated ampacities (blue line is barely visible due to overlaps).

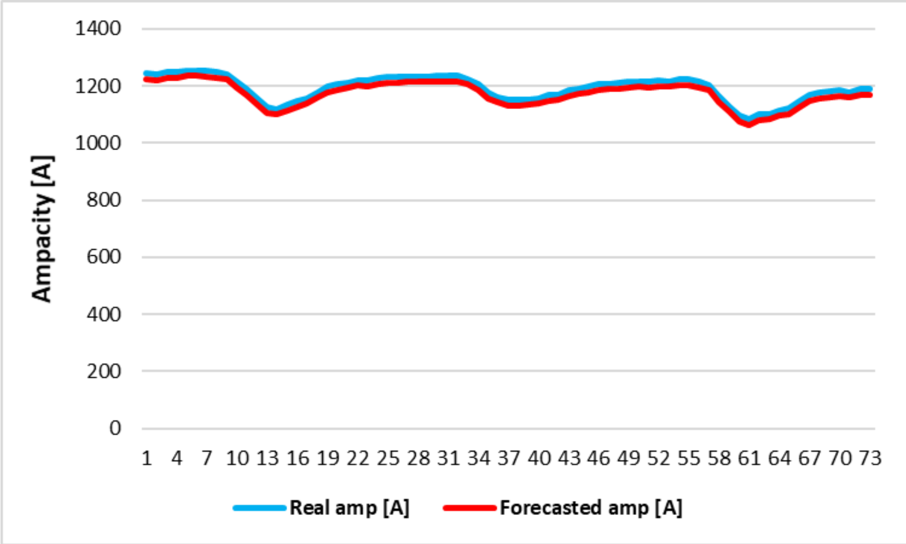


Figure 6-13 – Ampacity forecasts – internal line

However, there were two goals that were put in front of this BUC. The first of these was development of the ANN for the ampacity forecasting, while concentrating on the internal line in the Bulgarian grid. That part was, as illustrated above, completed with high level of accuracy achieved. The second goal, however, was comparing the forecasted values of the ampacity with the static rating of the selected line in order to demonstrate the potential for the transmission capacity growth in case the forecasted ampacity is used. That comparison is shown (for the same 72 hours as in the previous diagram) in the Figure 6-14, where the green line illustrates the static rating of the 220 kV OHL SS Plovdiv – SS Aleko.

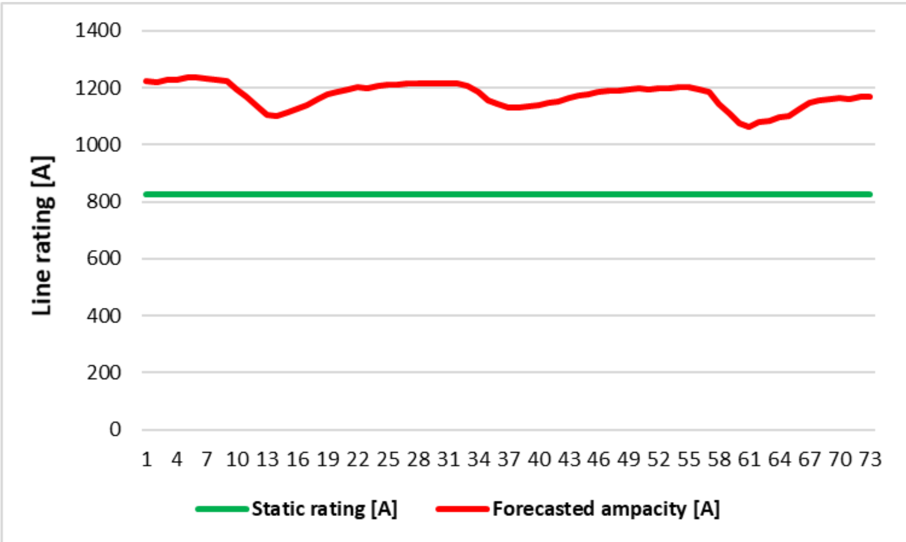


Figure 6-14 – Ampacity comparison – internal line

From this diagram, it is obvious that the application of the ANN-based forecasts could indeed increase the energy transfer capacity over the selected internal line. On average, the increase of the capacity of this line in the chosen three-day period was equal to about 42%. Of course, it can't be claimed that this would be the case for any time period, but it is a good indicator of how big the potential for usage of this technology on the selected OHL is. A list of KPIs for this BUC can be seen below, in the Table 6-4.

Table 6-4 – KPI definition – BUC 04

KPI number	KPI name	Target value
BG-BUC04.01	Internal line rating increase [%]	> 0%
BG-BUC04.02	Reduction in internal line loading [%]	> 0%

As the capacity over the selected period of 72 hours was greater than 40%, it is clear that the first KPI was fulfilled in this BUC. Regarding the second one, it directly depends on the line rating, since loading of the line gets calculated as the ratio of the current flow through the line and the rating of that line. Since the higher rating of the OHL means the lower percentual loading (in case in which current stays the same), it can easily be concluded that the successful reaching of the goal set for the first BUC also meant that the target defined for the second KPI in this BUC was also reached. This was per se enough to declare the BUC 04 a success and to move on to the BUCs that had its finalization defined as one of the necessary preconditions for the start of any actions. Moreover, stated success of this BUC can also be observed through the prism of the ANN development, only strengthening the provided statements.

6.5 BUC 05 - Results

Continuing to build upon the foundation that has been set by the previous BUC and the work done in it, BUC 05 of the Bulgarian pilot was the one that needed to focus on the application of the developed ANN-based forecasting algorithm on the interconnections between the Bulgarian system and systems around it. Here attention needs to be drawn to two major points that are relevant for this Use Case:

- First, the data that was at the disposal of the partners was strictly the one related to the Bulgarian parts of lines in the grid. In case this algorithm would be practically used, it would be absolutely necessary to ensure that the other TSO owning the part of the observed line also applies similar technique for ampacity calculation and that the results of the two calculations are aligned. In any other case the full available potential of proposed solution would not be implemented properly.
- Second, it needs to be underlined that the application of the ampacity forecasting on the tie-line only would not per se mean the increase of the net transfer capacity between the two countries that are connected by that line. It can happen, in practice, that the limiting grid element that gets congested is not an interconnector (or a tie-line, as it is also called), but some internal transformer or line in one of the grids. However, by applying BUC 04 and BUC 05 on the critical grid elements, users could utilize all necessary ampacity forecasts to adequately estimate the impact on the net transfer capacity and the possibility of additional energy getting exchanged between the systems.

For the demonstration of the technique described within the BUC 04 on the interconnections, 400 kV OHL between SS Thessaloniki in Greece and SS Blagoevgrad in Bulgaria was selected. For it, however, the entire procedure of creating the needed dataset of ampacities for training and testing ANN had to be repeated, but with the new data this time. Necessary meteorological data was already at disposal of the TSO, so the procedure could be conducted without any major issues. Based on this dataset, the ANN configuration consisted of 5 layers with [32, 24, 16, 12, 6] neurons. By applying this configuration for the forecasts of the line ampacities, MAPE value of only 0.76% was achieved. To illustrate this level of matching between the forecasted values and the values that were calculating by utilizing formulae, diagram shown in Figure 6-15 was made, with blue and red lines matching almost perfectly once again.

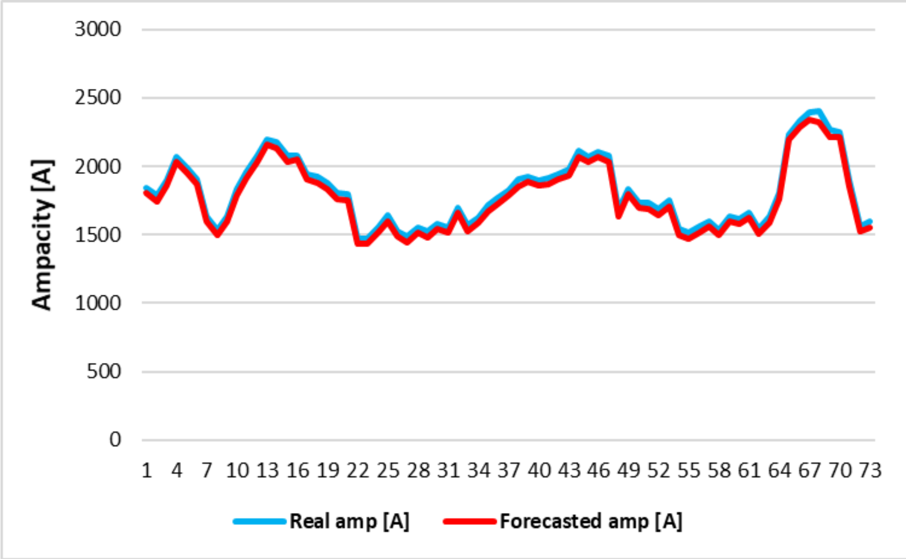


Figure 6-15 – Ampacity forecasts – interconnector line

Aside from the clear close-to-perfect match of the forecasted values of ampacities and the values that were calculated by using the equations from the standard, there should also be (in line with the form utilized in the BUC 04) a highlight placed on the differences between the forecasted ampacities of this OHL and the static rating that is commonly used for it in the Bulgarian grid's operation. This highlight is given in the form of the Figure 6-16, in which the red line again shows the forecasted values of this line's ampacities, whereas the green line serves as a marker of the static rating relevant for this line.

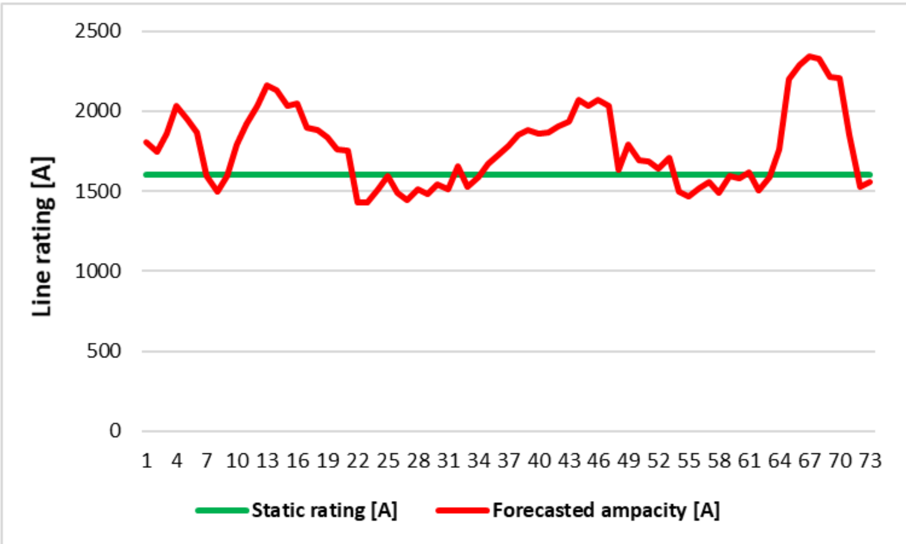


Figure 6-16 – Ampacity comparison – interconnector line

The situation shown in this diagram is a bit different from the one that was relevant for internal line, as here there are also some situations in which, due to slightly worse climatic conditions, forecasted ampacity actually goes even below the static one. Although the main point is still that the ANN-based forecasts of ampacities averagely exceeded the static ratings by 10.7%, it is also worth noting that the application of these forecasts could also improve grid's reliability in cases in which the actual ampacity is lower than the regular static rating of the OHL. KPIs for this BUC can be found below, in Table 6-5.

Table 6-5 – KPI definition – BUC 05

KPI number	KPI name	Target value
BG-BUC05.01	Interconnector rating increase [%]	> 0%
BG-BUC05.02	Reduction in interconnector loading [%]	> 0%

By using the same logic as in the previous case, it can be stated that both of the listed KPIs have been achieved successfully. In addition to this, there are also another two points that should be raised when it comes to the interconnector lines and the application of the developed algorithm for them in future. First, it should be highlighted that the ANN-based forecasts can be applied both in cases when the SO calculates the available capacity on border, and in cases in which that is done by the Regional Security Coordinators (RSCs), making this asset rather worthy for both of these potential users. Second, ANN-based forecasts of the ampacities can be applied both if standard NTC (net transfer capacity) approach is used, an in cases when the flow-based methodology is applied, so picking one of these techniques does not harm the relevance of the developed solution. Thus, this BUC was also successfully finalized.

6.6 BUC 06 - Results

As said in the introductory chapter of this report, along with the forecasting part of the pilot, there is also another part that has not been referred to yet – the part related to optimization of connection points of variable RES and battery storages. It should be clarified why was it even desired to attempt to use the optimization techniques for this, when it was done just fine by the TSOs manually before. However, increase in the number of requests for connections made it difficult to properly consider all relevant factors and to assess all combinations of connection points when more than one request is examined at the same time. This is where the optimization techniques could step in and assist the TSOs. To illustrate this, it was necessary to pick the facilities for which the process of selecting the connection points would be simulated. The initial idea was to use the real connection requests, but that was not possible due to data confidentiality. As a back-up option, virtual facilities were used. This was satisfactory, as the point of this BUC was not to actually determine the connection points, but to demonstrate potential that the optimization methods have for helping in this step. This could be done with the virtual facilities just as fine. Those facilities are shown in the list:

- WPP 1 – 40 MW of installed capacity;
- WPP 2 – 40 MW of installed capacity;
- WPP 3 – 50 MW of installed capacity;
- Battery storage – 30 MW in charging mode and 30 MW in discharging mode.

Together with the facilities for which the connection points would be optimized, it was also essential to select the region of the grid in which those units could be connected at all. For that, the part of the 110 kV grid in Bulgarian system has been picked, as shown in the diagram provided in the Figure 6-17.

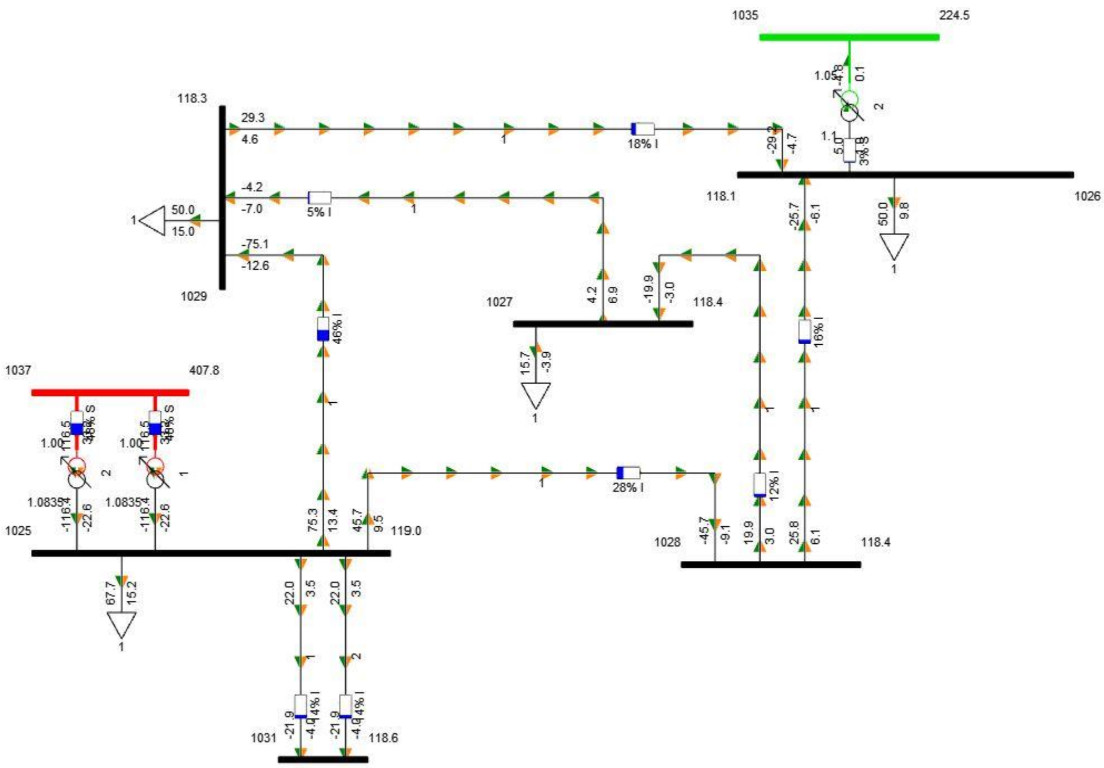


Figure 6-17 – Part of the 110 kV grid of interest (before connection)

The form of the used diagram here is the standard one from the PSS/E tool. Moreover, it was needed to choose the optimization criterion that would be applied in order to rank the potential solutions and to decide upon the best one. For that goal, the minimization of the average percentual loading of the lines in this area was picked. Of course, it would be possible to modify the code to work with the other optimization criteria as well (depending on the preferences of the users), but this criterion was found to be fitting for demonstration purposes. The lines for which the average loading was monitored were:

- line 1025-1029 (1);
- line 1025-1031 (1);
- line 1025-1031 (2);
- line 1025-1028 (1);
- line 1026-1028 (1);
- line 1026-1029 (1);
- line 1027-1028 (1);
- line 1027-1029 (1).

It is noticeable that the nodes and branches connecting them were referred to by their number in the PSS/E model. This was necessary due to data confidentiality issues, as the network model of ESO EAD is not publicly available, so there was no option to show even the parts of it with the actual names or even with such a level of characteristics that would allow the identification of the parts of the grid. In this BUC, however, this was also deemed not vital to the success of the procedure, as it didn't prevent the algorithm from optimizing the connections of the facilities to the nodes addressed by the numbers.

As the potential connection points in the observed parts of the grid, five nodes were selected – 1025, 1026, 1027, 1028, and 1029. With that elaborated, it was time to choose the optimization technique that would be adequate for the task. For that, the genetic algorithm was picked. This technique is well known in the expert circles, owing its reputation to the efficiency, the reliability, and the possibility to reach global optimums of even the most complex problems. Also, it's been tested again and again for usage in problems related to the power system, passing with flying colours every time. However, there was one problem before the optimization was conducted – genetic algorithm works with the solutions represented in the binary form, as a group of zeros and ones. Hence, it was necessary to find the way to represent the solutions of the connection-related problem, each being one combination of points for connecting the facilities to the grid, in the binary form. This was resolved by using the format given in the Figure 6-18. It can be seen that each of the solutions had 20 bits, each with the value of zero or one. Number 20 was calculation as the product of multiplying the number of facilities and the number of the potential connection points. Therefore, the first five bits were dedicated to WPP 1. Out of those five bits, only one could have the value of 1. The position of that 1 indicated the connection point of the first WPP. If, for example, 1 in the first five bits would be on the second position, that would mean that, in that solution, WPP 1 would be connected to node corresponding to position 2, i.e. node 1026. This principle was also used for the other bits, with the bits from 6 to 10 and from 11 to 15 dedicated to WPP2 and WPP 3, respectively, while the final five bits indicated the position of the battery storage.

0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0

Figure 6-18 – Representation of the solutions in GA

For example, the solution shown in the figure above (in which different colours were assigned to each of the facilities, making the process easier to follow) would mean that WPP 1 would be connected to node 1026, whereas both WPP 2 and WPP 3 would be connected to node 1029. Finally, battery storage would be connected to node 1025. There was also one more tricky point that needed to be addressed before the optimization. Namely, genetic algorithm, when going from one iteration to another, has to perform the operations to create "children" from the material of "parents". Two most commonly used operations are crossover and mutation. In crossover, two "children" get created from two "parents", by using different parts of "parents" to generate "children" (if the first "child" is made from the first sequence of bits from the first and the second sequence of bits from the second "parent", the second "child" will be created by combining the sequences not included in the first one). Here, attention was paid to ensure that, when doing the crossover, the rule that one facility can only have one connection point was still enforced. In the mutation process, one "parent" generates one "child", which is typically achieved by switching places of two bits in "parent". Same as with the crossover, attention was paid to ensure that the newly generated solutions were still valid. Finally, the measure of every solution, used for its ranking, was calculated in line with the Formula (6.5), in which the indexes *CH* and *DIS* mark the states of grid in which the battery storage was working in charging and in discharging mode.

$$F = \min\left\{\sum_{j=1}^{N_{line}} \frac{p_{jCH} + p_{jDIS}}{2 \cdot N_{line}}\right\} \tag{6.5}$$

Here, p marked percentual load of the line j, whereas N_{line} stood for the total number of observed lines (in this case, 8). To calculate the measure of the solution, the EHV-HV DT was utilized. In it, the script first simulated the connections of all facilities in line with the solution, with the battery in the charging mode. It was taken that all units work with installed capacity, with the same being valid for the battery as well. From this, p_{jCH} values could be taken. Then the same was done for battery in discharging mode, giving the p_{jDIS} values. Hence, by using Formula (6.5), the measure of that solution could be calculated. In the optimization process, the number of iterations was set to 100, with the size of population also being 100. Crossover and mutation rates were adopted as 0.8 and 0.1, respectively. The solution in the final population that had the lowest measure value was the one declared optimal in the end. To increase precision of the process, principle of elitism was also used, with the two best solutions from the previous iteration not getting subjected to the operations when moving to the next generation. By using the developed algorithm, the optimal solution provided in the Table 6-6 has been obtained. For this configuration, the average loading of eight observed lines was equal to 13.42% in the selected hour. That hour has been chosen as one of the 72 hours for which the previously described forecasts were conducted. Flows obtained for the optimal solution (battery charging) are shown in Figure 6-19.

Table 6-6 – Optimal solution of the problem

Facility	Connection Point
WPP 1	1026
WPP 2	1029
WPP 3	1026
BESS	1025

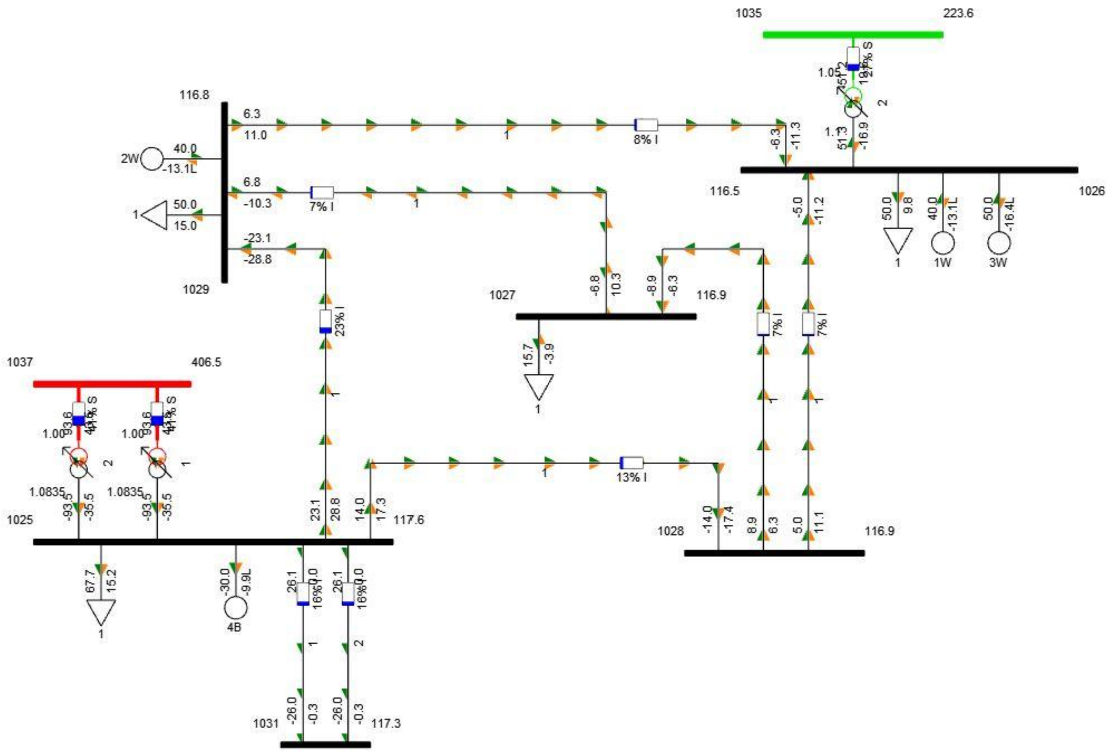


Figure 6-19 – Part of the 110 kV grid of interest (battery charging)

It can be seen that the loadings of the lines are indeed quite low for the proposed configuration of the grid. The same can be said for the case when the battery in discharging mode, shown in Figure 6-20.

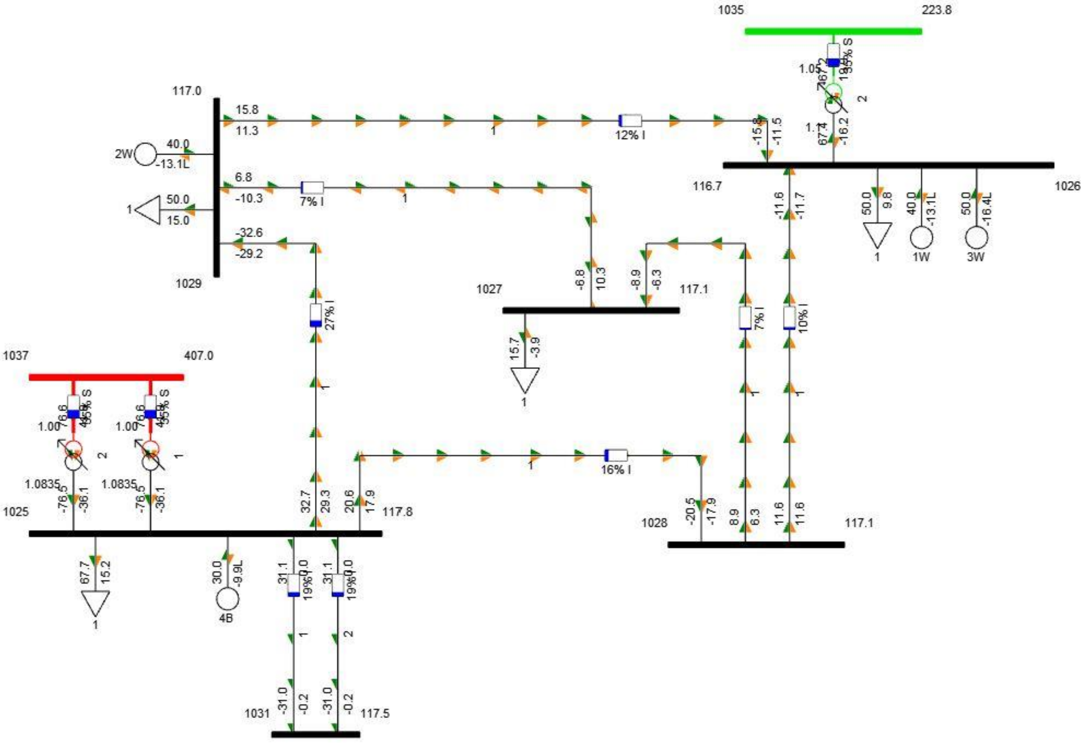


Figure 6-20 – Part of the 110 kV grid of interest (battery discharging)

In order to illustrate the effect that connecting the facilities in accordance with the suggested solution would have on the grid even better, percentual loading of every line shown in the two diagrams above has been extracted and put in the made-for-purpose tabular form. That form is provided in Table 6-7.

Table 6-7 – Line loadings in the optimal configuration

Line	Loading – charge [%]	Loading – discharge [%]
1025-1028 (1)	13.3	16.3
1025-1029 (1)	22.8	27
1025-1031 (1)	16	19
1025-1031 (2)	16	19
1026-1028 (1)	7.4	9.9
1026-1029 (1)	8	12.1
1027-1028 (1)	6.6	6.5
1027-1029 (1)	7.4	7.4

These loadings correspond to the average value obtained as the value of the measure of the solution declared optimal after the completion of the optimization procedure. The validity of this solution has also been verified by the manual testing, where random solutions were generated and compared to the suggested one, with the suggested one turning out to be better than any other generated solution. This was taken as the proof of the accuracy of the developed technique. In cases in which there would be more potential connection points and/or more facilities, there might be a need to modify the code in order to include more generations or larger populations, but doing that in this case was not needed and would only lead to the process consuming more time and resources than it did with the selected parameters. Namely, the whole process here took only several minutes, being as efficient as possible for the algorithm of this size and complexity. KPI that has been defined for this BUC is enclosed below.

Table 6-8 – KPI definition – BUC 06

KPI number	KPI name	Target value
BG-BUC06.01	Number of optimized connections [#]	> 0

Before moving on to evaluating whether or not this KPI reached its designated target value, it should also be stated that the selection of the types of the virtual facilities could have been done differently in order to include conventional units or solar parks as well. However, this would not change the main conclusions and the outcomes of the work invested in this BUC. Those outcomes are that connection points were optimized for four facilities (albeit virtual), which is fully aligned with the higher-than-zero criterion defined for the KPI. In accordance with this, it could be said that BUC 06 of the Bulgarian pilot has been successfully completed. Not only that, but, as this was the only BUC that dealt with the scope of Task 7.5 of the TwinEU project, its success also meant the end of that task and the completion of the foreseen activities related to it. With that out of the way, the focus switched back to Task 7.4 and to the UCs related to it, as will be thoroughly described in all of the remaining sections of this chapter.

6.7 BUC 07 - Results

With the only BUC dealing with Task 7.5 out of the way, the work could return to the Use Cases which are related to Task 7.4 of the TwinEU project. The first of these was the BUC 07, in which assessment of the HV grid's reliability was to be tested. This was supposed to be done by conducting the so-called "N-1" analysis on the grid in the selected operational regime, after which the issues could be identified and proper solutions for them suggested. N-1 assessment, by definition, includes simulating outages of every single element (here it was limited to the lines and transformers) in the grid and running the load-flow calculations on the system states created in such a way. This allows the system operator to check if there could be problems related to line overloading or detection of voltages out of the defined range in case some unplanned outage in the grid happens. Since this BUC has been performed on the EHV-HV DT developed in the Bulgarian pilot, the system operator in question here was Bulgarian TSO.

For these calculations to be possible, it was necessary to first adjust the mentioned DT. This was done by taking, as stated under the description of the effort invested in BUC 01, base grid model that was delivered by the Bulgarian TSO. After that, the forecasts were conducted for the same 72-hour-period for the production power of SPP Karadzholovo, production power of WPP Sveti Nikola, and ampacities of the selected overhead lines. 72 separate grid models were created, one for each of the hours in the simulation period, and appropriate forecasts were inserted as inputs into those models. After this was done, it was possible to select one of those hours and to run the N-1 assessment on it. This simulated the actual actions that would be taken by the TSO that obtained the forecasts. In real-life case, hour for which the calculations would be done would be chosen based on the actual operational conditions of the system and the experience of the SO employee participating in the process. Since the outputs of the Python and R scripts are 72 hourly models, it wouldn't be necessary for the SO to be limited to one hour either. It would be possible to do these assessments on each of the 72 hours well in advance, highlighting any potential issues that may occur in the system and giving the operator necessary time to plan actions and, in case a need arises, conduct those actions to mitigate or entirely avoid problems.

In order to illustrate this, one of the hourly models with the included forecasts of relevant parameters was selected and assessment was run on it. The hour (one out of the 72) was selected in cooperation with the TSO partners as fitting for the needed demonstration purposes. The results obtained in this way can be found in the Table 6-9, in which the left column shows the outage for which the problems were detected, whereas the middle column lists the overloads that were detected for those outages.

Table 6-9 – N-1 assessment results

<table>
<tr><th>Outage of element</th><th>Overloaded element</th><th>Corrective action</th></tr>
<tr><td>Line 1002-1013 (1)</td><td>Line 1002-1013 (2)</td><td>Switching off the overloaded line</td></tr>
<tr><td rowspan="2">Transformer 1015-1013 (1)</td><td>Transformer 1015-1010 (1)</td><td rowspan="2">Switching off the transformer 1015-1010 (1)</td></tr>
<tr><td>Transformer 1013-1010 (1)</td></tr>
<tr><td>Line 1025-1028 (1)</td><td>Line 1025-1029 (1)</td><td>Switching off the line 1026-1029 (1)</td></tr>
</table>

First of all, it should be emphasized that the identifiers of the lines and transformers had to be reduced to numbers of nodes connected by them and, in brackets, the circuit identifier which is relevant if two or more branches connect the same two nodes. This manner of nomenclature had to be used for the same reasons for which the node names in BUC 06 were converted to the numbers given to them in the PSS/E model – data confidentiality. As the grid model of the Bulgarian TSO is not publicly available, it was not possible to provide the information included in that model in this report. However, by using the identifiers in forms of node and circuit numbers, the main outcomes and conclusions could still be presented, but with the privacy of the data still kept intact. The second point that should be underlined is the rightmost column of the table with N-1 results. Namely, in line with the propositions of this BUC, it was not enough to merely run N-1 assessment and determine if there were any issues. Adding to it, it was also necessary to suggest some of the corrective actions that the TSO could take to mitigate or completely avoid the problem in the grid. In case none of those could be found, it was also permitted to propose the new project that would need to be commissioned in the grid in order to permanently fix the spotted issue. However, for all four overloads that were noticed in the selected hour, corrective operational measures were found that not only removed the congestion, but also ensured that there were not any other congestions caused by applying them. To do this, it was first needed to determine the cause of the issue and the way in which the simulated outage affected the flows in the grid, leading to the spotted overload. After that, different potential solutions for every problem were tested until one that showed the best results was selected and inserted in the table with the results. This process could be done for the voltage related issues as well, but none of those were seen in any N-1 analyses performed for the selected hour. To illustrate the way the flows in the grid change after some outage in it happens and how the suggested corrective action fixes the issue, series of diagrams with the flows were made in the PSS/E tool, showing the base case (pre-outage state) at location of the spotted issue, the situation after the outage, and the situation after the suggested corrective action is taken. Starting this, Figure 6-21 gives insight into the base case state of grid part relevant for the 1002-1013 outage, with bars at the middle of lines and transformers showing their percentual loadings in observed hour.

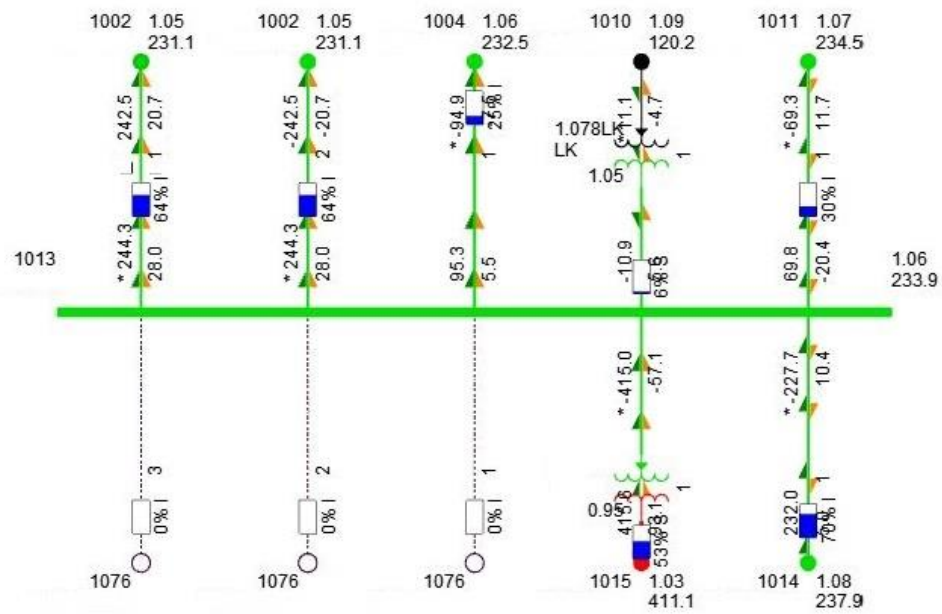


Figure 6-21 – Outage 1002-1013 – base case

It can be seen from this diagram that there are two direct lines going from the node 1002 to the node 1013, with the loading of each of them being equal to 64% of their respective ratings. After one of the two lines switches off, the congestion of the other one happens. Percentual loadings of the branches in the relevant part of the grid can be seen in the Table 6-10 for the situation after the outage. In this table, the line for which the outage has been simulated (line marked as 1002-1013 (1)) is also included, but its percentual loading (due to it being out of operation in this case) is simply put to the zero value.

Table 6-10 – Line loadings - outage 1002-1013 – N-1 case

Line	Loading [%]
1002-1013 (1)	0
1002-1013 (2)	109
1004-1013 (1)	31
1013-1010 (1)	6
1011-1013 (1)	39
1013-1014 (1)	70
1015-1013 (1)	50

It can be seen that the second line from node 1002 to 1013 gets overloaded in this case, since it needs to take over the flow that has initially been split between it and the line on which the outage occurred. It should also be noted that its loading is not entirely equal to the mere sum of the loadings of both of these lines in the base state of the grid, as it would be even higher than what is shown here (it would be equal to about 128%), which means that some of the loading is also taken over by the other lines in this part of the grid. These flows and loadings can also be seen in a graphic manner in Figure 6-22.

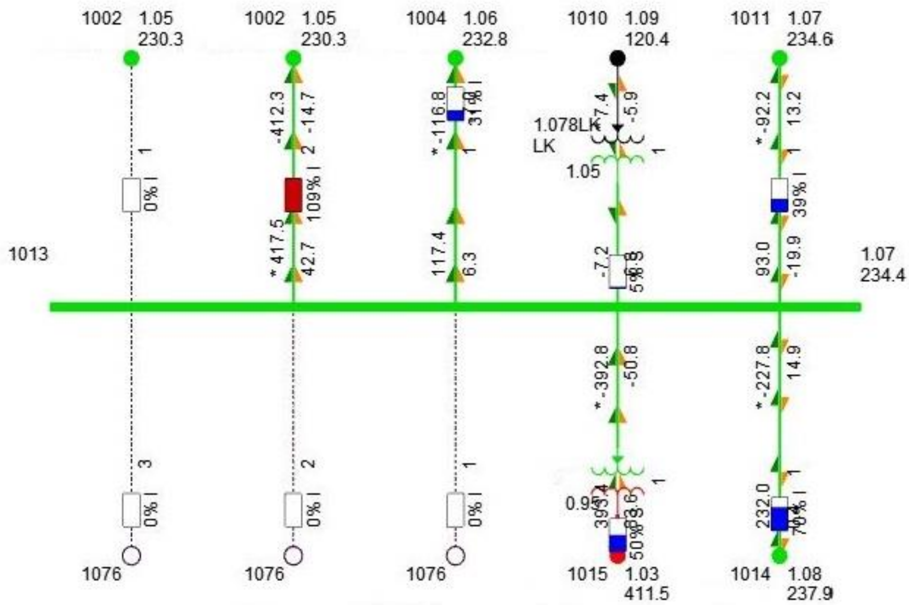


Figure 6-22 – Outage 1002-1013 – N-1 case

Once the outage of the targeted line happens, the suggested corrective action (consisting of switching off the overloaded line as well) needs to be taken in order to relieve the problem. Before suggesting this solution, it was also necessary to check in the model if no other issues would arise if this measure gets applied. As this was not the case, the solution was deemed valid. Better insight in the distribution of the flows once the corrective action is taken can be obtained by examining the percentual loadings of the rest of the lines once the line 1002-1013 (2) gets switched off. Those are shown in Table 6-11.

Table 6-11 – Line loadings - outage 1002-1013 – corrective action

Line	Loading [%]
1002-1013 (1)	0
1002-1013 (2)	0
1004-1013 (1)	64
1013-1010 (1)	9
1011-1013 (1)	93
1013-1014 (1)	71
1015-1013 (1)	33

By comparing these values with the values from the Table 6-10, one could easily spot the differences in the loadings of the remaining lines, which is especially visible for the lines between the nodes 1004 and 1013 (which went up from 31% of loading to 64% of loading), and the nodes 1011 and 1013 (that went from 39% of loading to 93% of loading). However, none of those values exceeds the upper limit of the line loading in this case, meaning that no additional issues were caused by applying the solution. The loadings from the previous table are also visible in the diagram made for this case, shown below.

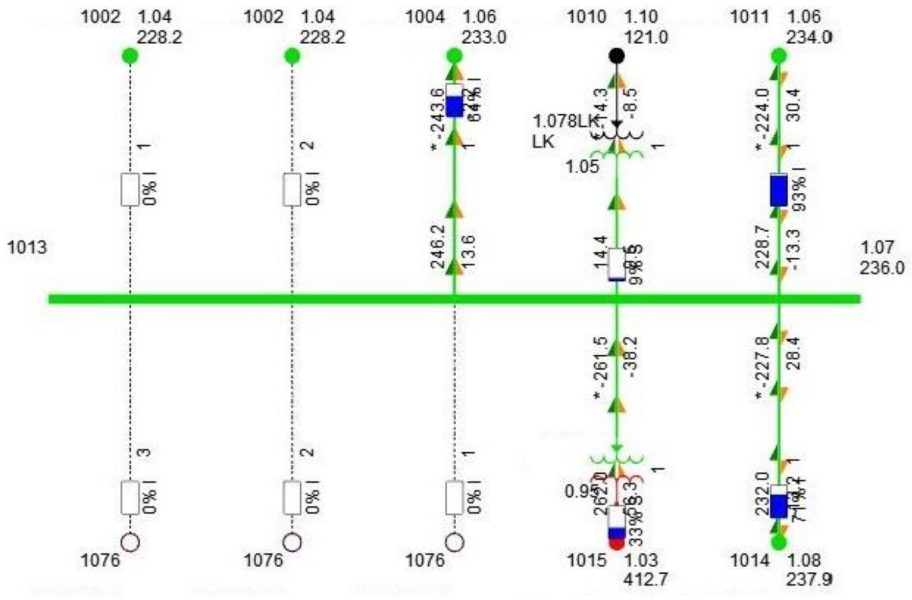


Figure 6-23 – Outage 1002-1013 – corrective action

From this diagram, it is once again clear that the proposed corrective measure actually had the desired effect. In the similar fashion, the detailed analyses were conducted for the outage of the transformer 1015-1013 (named in an inversed fashion due to node 1015 being on a higher voltage level than node 1013). Load flows in base case state for this part of the grid are shown in the diagram in Figure 6-24.

From this figure, it can be seen that the flow through this transformer (that connects 400 kV and 220 kV voltage levels) goes from the higher to the lower voltage, but that there is also some flow from the 110 kV level to 220 kV level through the transformer 1013-1010. This proves to be quite relevant once the outage of the transformer 1015-1013 is simulated. This state of the grid is enclosed in Figure 6-25, with the detailed presentation of the loadings of most prominent branches preceding it as Table 6-12.

Table 6-12 – Line loadings - outage 1015-1013 – N-1 case

Line	Loading [%]
1015-1013 (1)	0
1013-1010 (1)	113
1015-1010 (1)	138
1002-1013 (1)	41
1002-1013 (2)	41

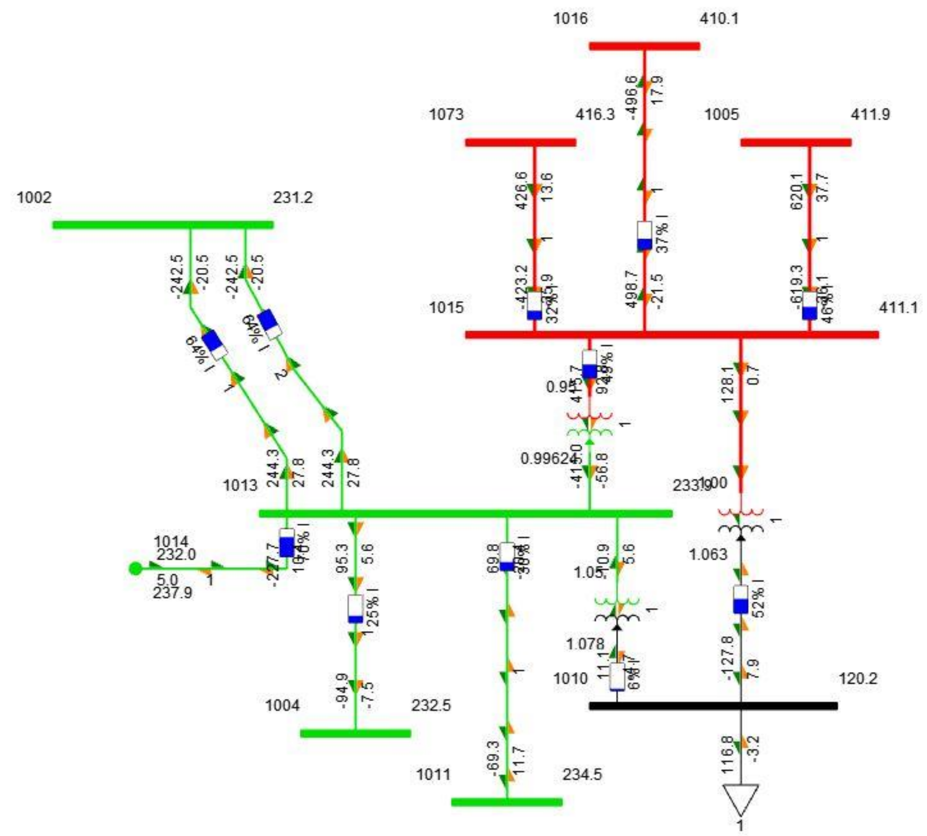


Figure 6-24 – Outage 1015-1013 – base case

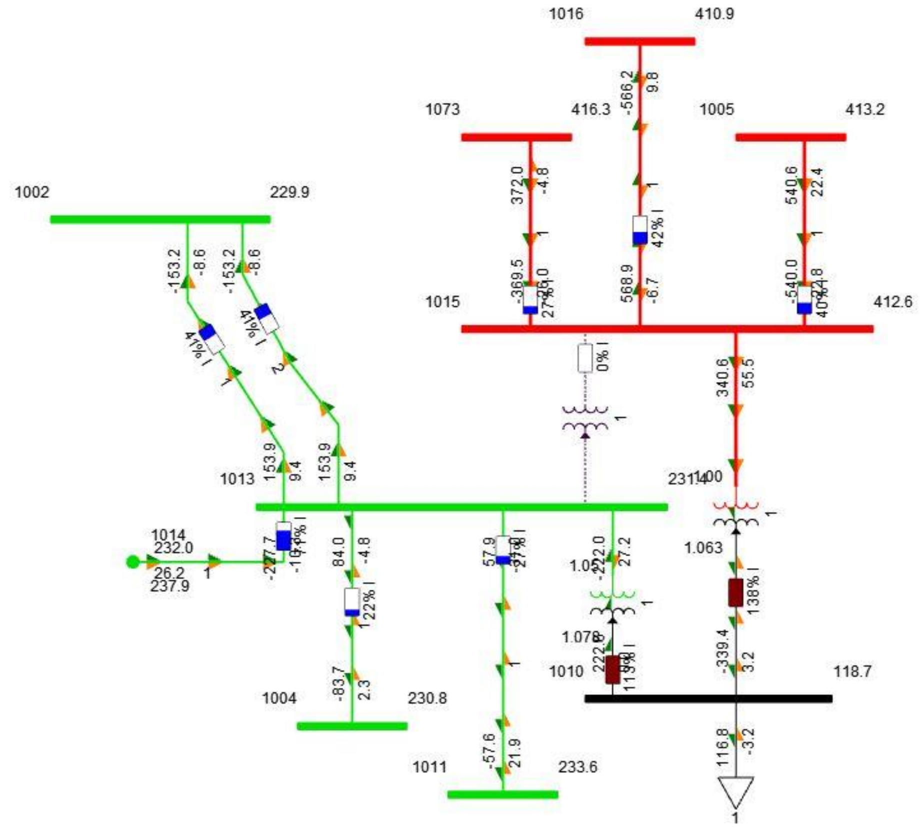


Figure 6-25 – Outage 1015-1013 – N-1 case

Here it is clear that the energy that initially went directly from the 400 kV to the 220 kV voltage level now goes via 110 kV bus 1010, overloading 400/110 kV and 220/110 kV transformers in the process. By switching off the transformer 1015-1010, this path of energy gets cut, which effectively resolves all of the spotted overloads. In addition to this, energy flow only gets redistributed among the remaining lines, so no new congestions get created. This state of the system can be seen in Figure 6-26, with the percentual loadings of the same lines listed in the Table 6-12 given once again in Table 6-13. From this table, it is clear that not only the loading of the previously overloaded transformer from node 1013 to node 1010 is now within the loading limits, but also that, due to the redistribution of the flows in the grid, the loading of two lines from the node 1002 to node 1013 went down from 41% to 9%, as these two lines were no longer utilized for transferring energy from the node 1015 towards the node 1002.

Table 6-13 – Line loadings - outage 1015-1013 – corrective action

Line	Loading [%]
1015-1013 (1)	0
1013-1010 (1)	60
1015-1010 (1)	0
1002-1013 (1)	9
1002-1013 (2)	9

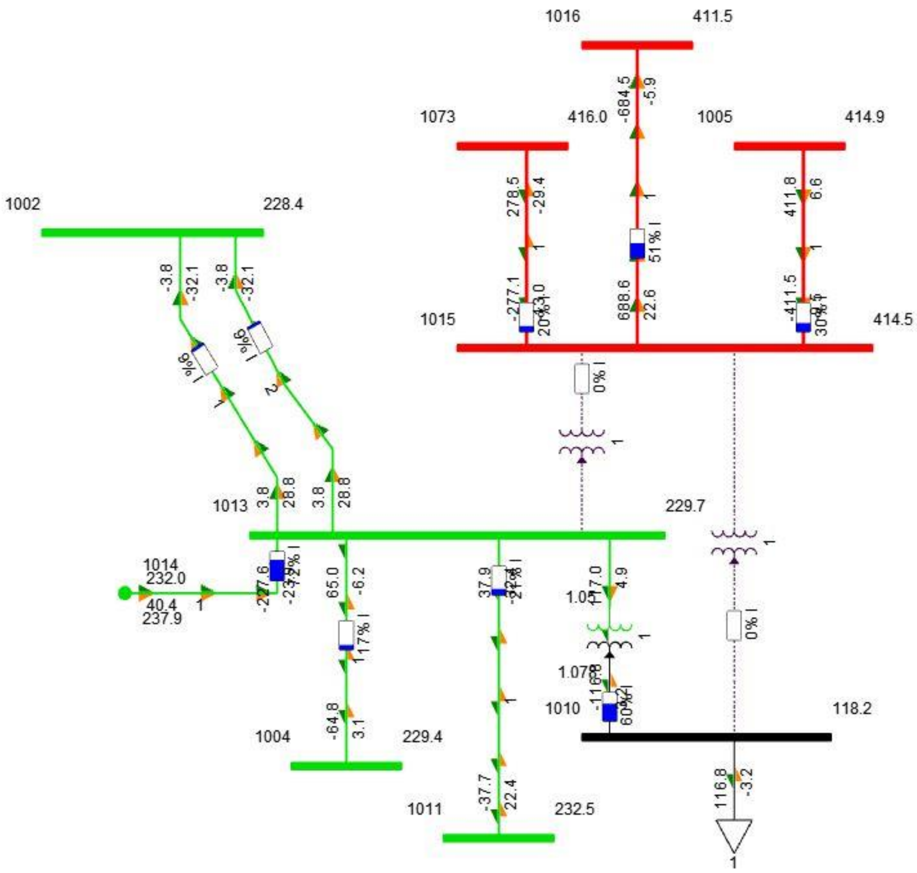


Figure 6-26 – Outage 1015-1013 – corrective action

This proves that the suggested measures were indeed appropriate and that the noticed problems can be resolved without constructing new infrastructure for energy transmission. To keep this subchapter at a reasonable scale, these diagrams weren't created for the third troublesome outage, but all of the conclusions valid for the former two can be applied to that one as well. As the descriptions of the run calculations and suggested actions are now completed, it is possible to move on to the evaluation of whether or not the KPIs that were defined for this BUC were reached. These KPIs are enclosed below.

Table 6-14 – KPI definition – BUC 07

KPI number	KPI name	Target value
BG-BUC07.01	Number of detected critical outages [#]	> 0
BG-BUC07.02	Percentage of considered congestions [%]	100%

For the first defined KPI, it is clear that, by detecting three critical outages for which the overloads are expected, value of this KPI went to three as well, so the goal was reached. In the similar fashion, it can be stated that all four of the spotted overloads were considered, with the adequate corrective actions suggested for each of them. Hence, the value of the second selected KPI here was indeed 100%, which means that the target value was achieved there as well. Since both of the defined KPIs reached values equal to (or greater than) their respective goals, it was also possible to state that BUC 07 was finished successfully, i.e. that the N-1 risk assessment of the transmission grid was performed in a proper way.

6.8 BUC 08 - Results

As was stated in the descriptions provided in the Chapter 4, BUC 08 was intended to extend the BUC 07 and to build upon the N-1 assessment that has already been conducted as a part of that BUC. For that to happen, it was necessary to create a situation in the grid that would, by itself, not consider the normal topology of the grid before running the full N-1 calculations. By doing this, it was possible to simulate the situation in the system in which there are two elements that are out of operation at the same time and to check if there are some problems related either to the overloads of the lines in the grid or to the voltages of the buses being out of the defined ranges. Speaking in general, this situation could be based upon several states that the system might encounter in the normal operation. Among those situations could, for instance, be the heavy blizzards that can sometimes occur during the winter months. Under those climatic conditions, it wouldn't be uncommon that two (or even more) elements go out of operation simultaneously due to the heavy icing combined with the high speeds of the wind.

However, for this BUC, much more common state of the system was considered. It is well-known that the state of the elements of the power system degrades due to the passage of time and the fact that some of those operate over 50 years without any action taken on them. This deterioration can also be sped up due to the adverse weather conditions, or due to human factor (construction works, crashes of the agricultural machines with the OHL towers, thefts, etc.). All of this makes it absolutely necessary for the SO to plan and perform maintenance of the elements on a regular basis in order to check the state and perform smaller repairs where needed. Maintenance, combined with major refurbishments and reconstructions, counteracts aging of the elements and prevents consequences that would come to be if no action was taken. However, although having some element under maintenance improves the system reliability on a longer time horizon, it temporarily acts opposite of that. When maintenance is performed on an element, that creates a N-1 situation in the grid for the duration of the works. In case another outage happens during that time, it puts the system in the state needed for this BUC. In line with that, this was the exact situation that was taken for this BUC. It was assumed that transformer 220/110 kV between nodes 1035 and 1026 was under maintenance, after which the N-1 assessment was performed. Since the hour taken here was the same as in the BUC 07, so it was expected (and, as it will be seen from the table, confirmed) that the issues seen there would be present again. However, there was also one entirely new problem in the grid that was entirely a consequence of the weakened state of it. All of the problems that were spotted in the conducted analysis are enclosed in the table.

Table 6-15 – N-1 results (TR 1026-1035 under maintenance)

<table>
<tr><th>Outage of element</th><th>Overloaded element</th><th>Corrective action</th></tr>
<tr><td>Line 1002-1013 (1)</td><td>Line 1002-1013 (2)</td><td>Switching off the overloaded line</td></tr>
<tr><td rowspan="2">Transformer 1015-1013 (1)</td><td>Transformer 1015-1010 (1)</td><td rowspan="2">Switching off the transformer 1015-1010 (1)</td></tr>
<tr><td>Transformer 1013-1010 (1)</td></tr>
<tr><td>Line 1025-1028 (1)</td><td>Line 1025-1029 (1)</td><td rowspan="2">Changing tap ratios on TRs 1037-1025</td></tr>
<tr><td>Line 1025-1029 (1)</td><td>Line 1025-1028 (1)</td></tr>
</table>

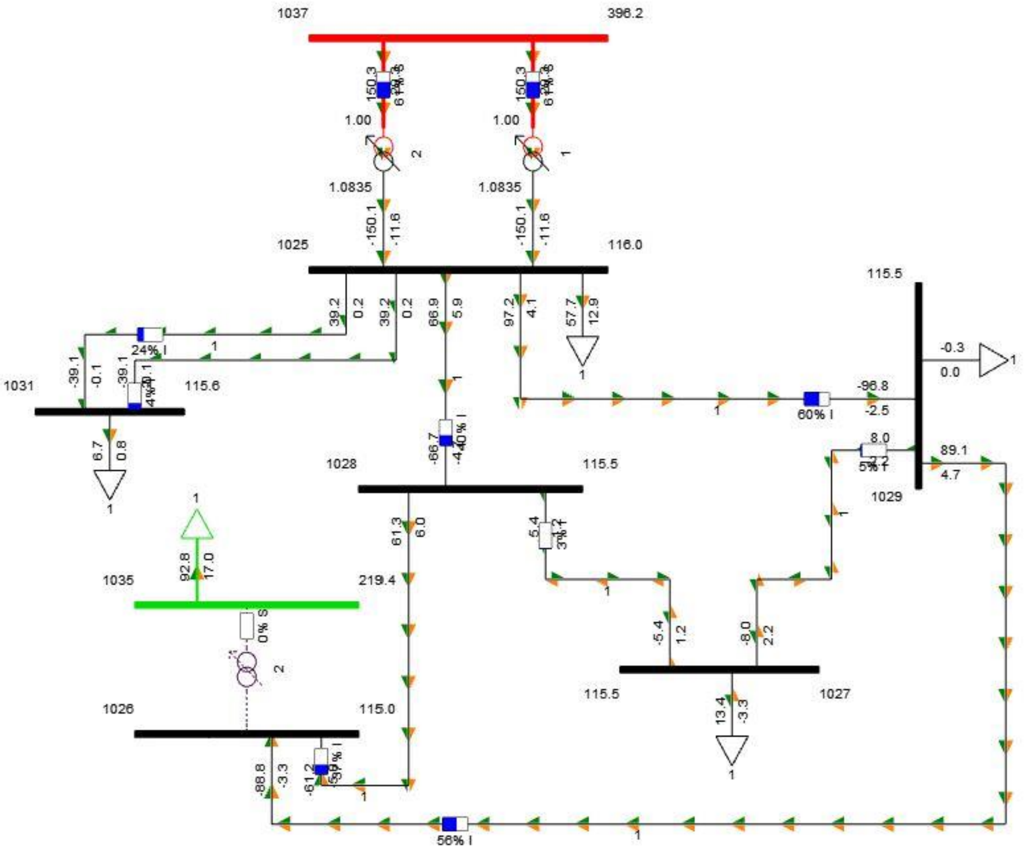


Figure 6-27 – N-1 with maintenance – base case

The first two outages (with three overloads caused by them) were already covered in the BUC 07, with the same corrective actions still being valid. The last two outages, however, should be explained more in detail here (one was covered already, but needs a different corrective action, while the other didn't appear in BUC 07 at all). In order to illustrate situation in grid (with transformer under maintenance) before the critical outage happens, single-line diagram provided in the figure below has been created.

It can be seen that, with only this transformer out of operation, there are no overloads in the observed part of the grid. This however changes once the line between nodes 1025 and 1028 gets switched off, since the line between the nodes 1025 and 1029 now needs to supply whole part of the 110 kV system together with all of the demand in it, leading to the overload. Diagram for this state is shown in Figure 6-28, with the Table 6-16, before that diagram, giving an insight into the loadings of the relevant lines.

Table 6-16 – Line loadings - outage 1025-1028 – N-1 with maintenance

Line	Loading [%]
1035-1026 (1)	0
1025-1028 (1)	0
1025-1029 (1)	103
1026-1029 (1)	65

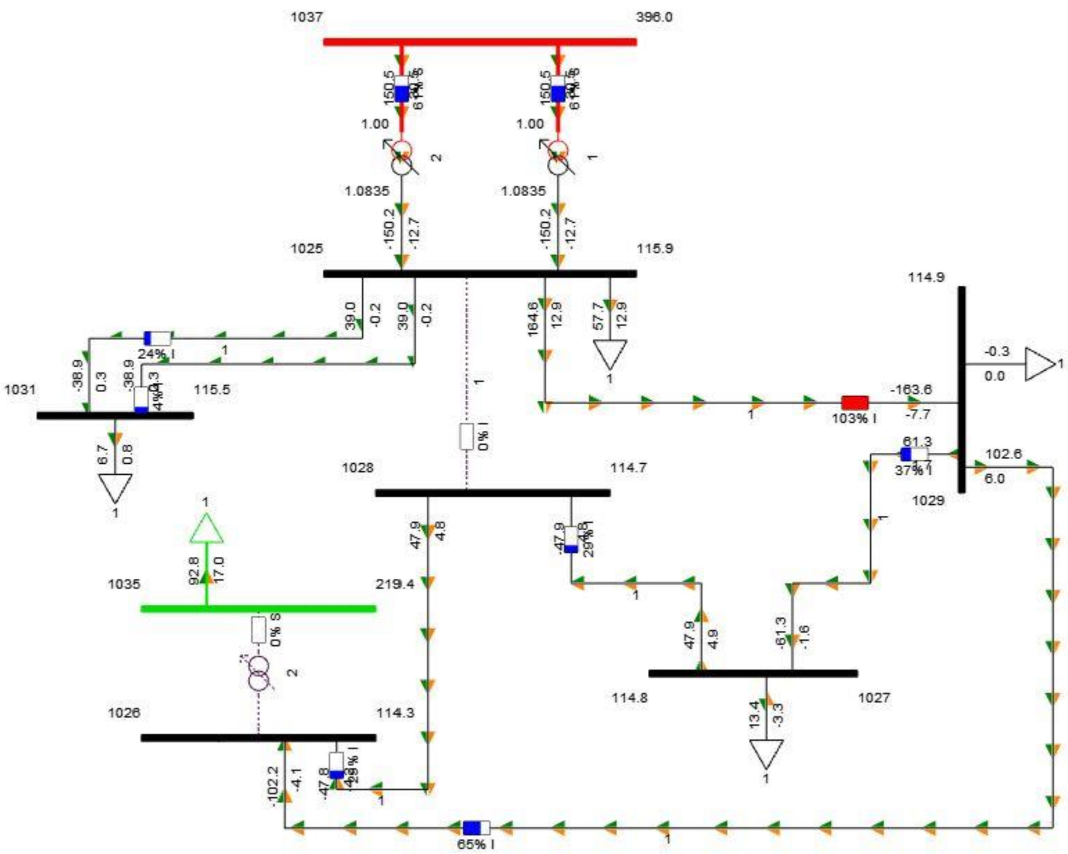


Figure 6-28 – Outage 1025-1028 – N-1 case (with maintenance)

This is the same issue that has been seen in BUC 07. However, there the corrective action that solved the issue was switching off the line between nodes 1026 and 1029, which was not applicable here due to the transformer 1026-1035 being out of operation as well. Thus, if the line 1026-1029 would also get switched off, the demand connected to the node 1026 would have no routes available for energy supply. Therefore, it was necessary to propose some other corrective action to mitigate the overload. That was, in this case, changing the tap ratios of the transformers between the nodes 1025 and 1037. The risk of applying this type of action was related to voltage values this time, as the tap ratio change could cause voltage values to go out of allowed ranges. However, this was not the case in this situation, as there were no voltages in the grid of interest that went out of range once the measure was used. The situation after this action is presented here, both in Table 6-17 (line loadings) and in Figure 6-29.

Table 6-17 – Line loadings - outage 1025-1028 – action with maintenance

Line	Loading [%]
1035-1026 (1)	0
1025-1028 (1)	0
1025-1029 (1)	99
1026-1029 (1)	62

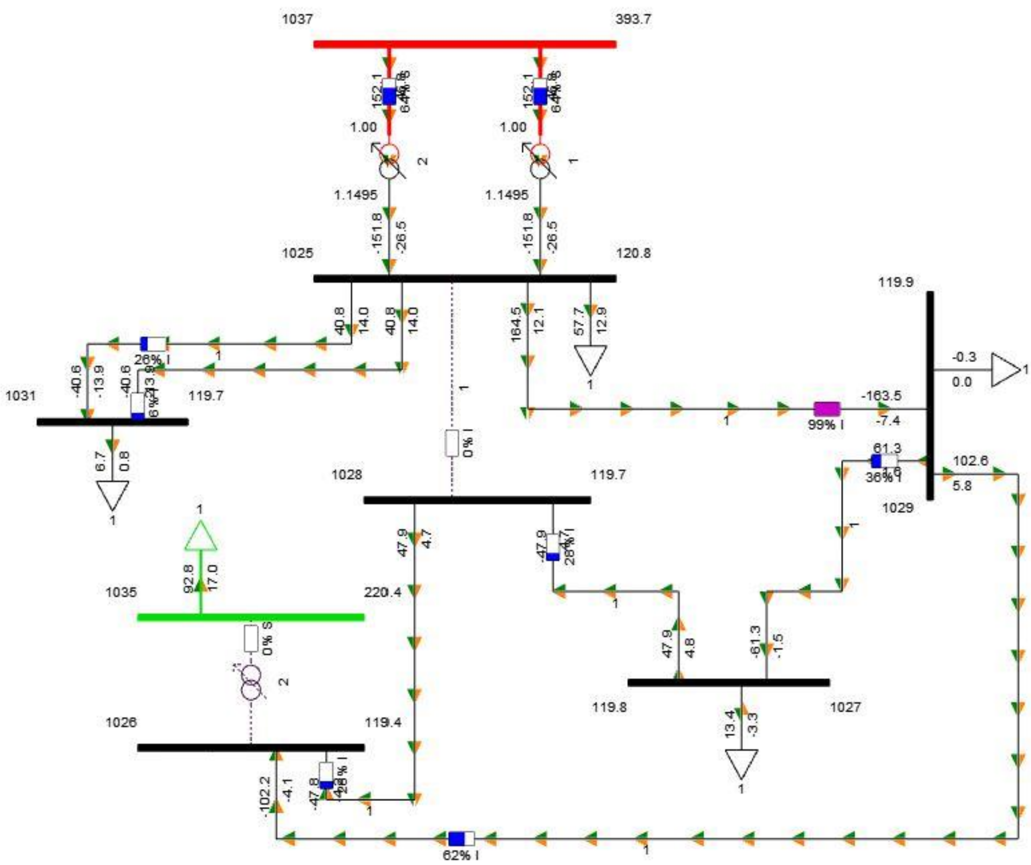


Figure 6-29 – Outage 1025-1028 – corrective action (with maintenance)

It is clear that this corrective action has the desired effects and that the issues in the observed part of the grid were indeed resolved. The other issue that has been spotted (and the one that did not exist in BUC 07) was the exact opposite of this one, with the line 1025-1029 being out of operation, and the line from node 1025 to node 1028 getting overloaded. The cause of this overload is pretty much the same as it was already described in the part of the text dedicated to the first spotted issue. It is thus related to the need to transfer energy from the node 1037, through the transformers connecting it to node 1028, and towards the demand supplied via the 110 kV grid in the observed area. Of course, any further outages could harm the security of the energy supply, thus having grave consequences. For the state of the grid in question after the line connecting nodes 1025 and 1029 gets switched off, line loadings are listed in Table 6-18, whereas the appropriate single-line diagram follows as Figure 6-30.

Table 6-18 – Line loadings - outage 1025-1029 – N-1 with maintenance

Line	Loading [%]
1035-1026 (1)	0
1025-1028 (1)	100
1025-1029 (1)	0
1026-1029 (1)	44

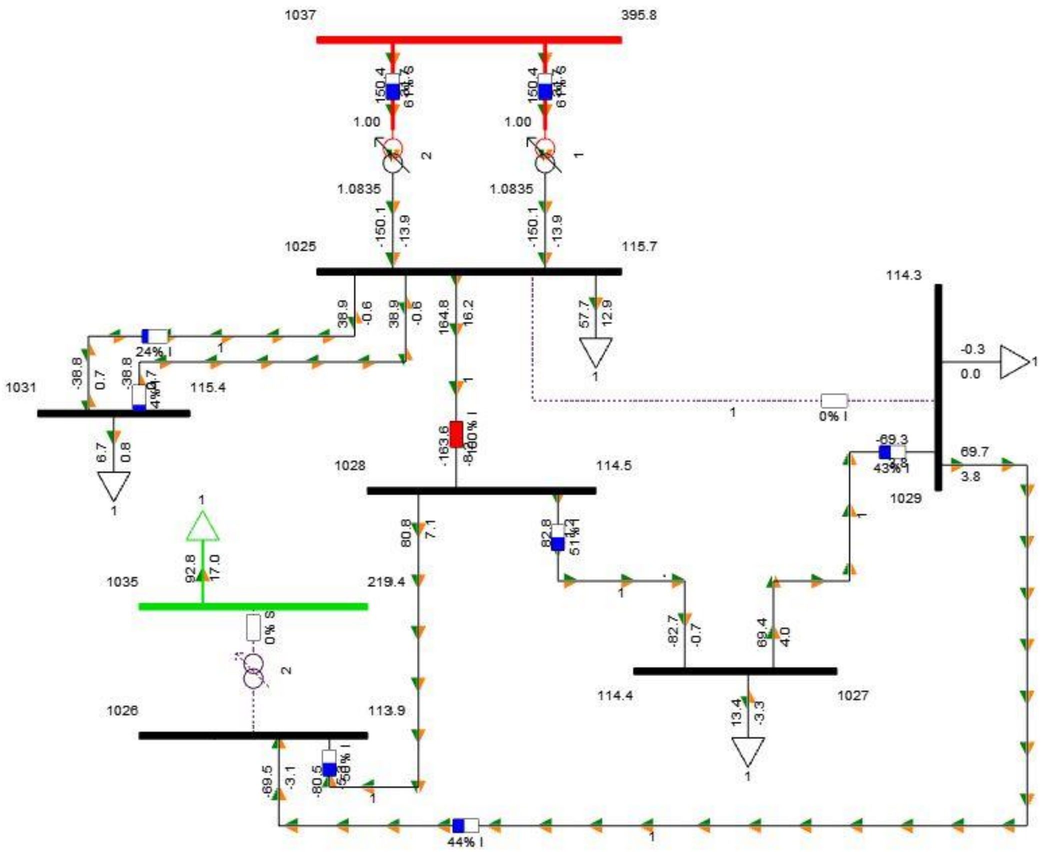


Figure 6-30 – Outage 1025-1029 – N-1 case (with maintenance)

It should be highlighted that, even though the table and the diagram show that the loading of the line 1025-1028 is exactly equal to 100%, the loading value was actually slightly over that. The 100% values shown were the consequences of the rounding procedure. The actual loading value of that line was in the range from 100% to 100.5%. Since the causes behind the analysed issue were exactly the same as for the previous one, a single logical first step was to try the same corrective action in order to resolve it. This meant that the attempt was made to modify tap ratios of the transformers between the nodes 1025 and 1037, increasing the voltages in the 110 kV grid in the process. This increase of voltages led to the decrease of current, reducing the loading of lines as well, thus making the proposed corrective action adequate for resolving the problem in question. The state of the grid after the corrective action is illustrated in the Table 6-19 (line loadings) and in the Figure 6-31 (a single-line diagram of the grid).

Table 6-19 – Line loadings - outage 1025-1029 – action with maintenance

Line	Loading [%]
1035-1026 (1)	0
1025-1028 (1)	96
1025-1029 (1)	0
1026-1029 (1)	42

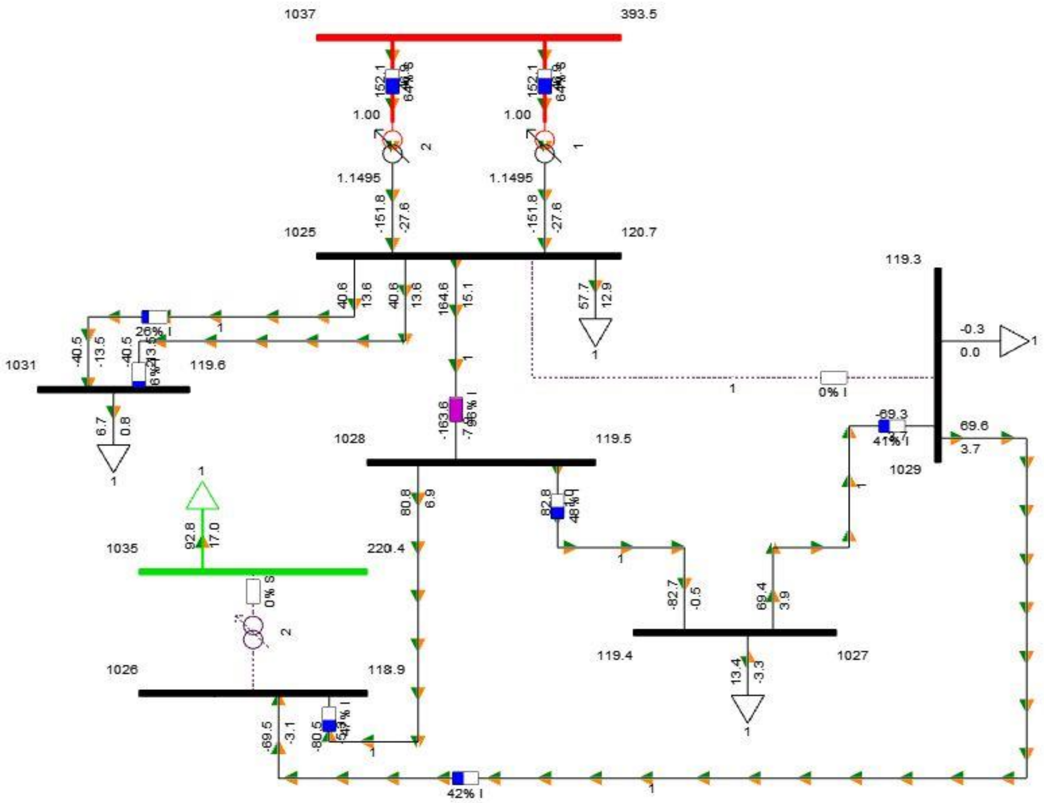


Figure 6-31 – Outage 1025-1029 – corrective action (with maintenance)

The fact that this outage caused an issue in this situation and not in the classical N-1 assessment only meant that this is a direct consequence of the transformer 1026-1035 being under maintenance. This can additionally be confirmed if one looks at the previous diagrams, where it is clear that, if there was no maintenance ongoing, the transformer would have helped in supplying the 110 kV grid. This is why it is crucial to conduct thorough checks when planning the works. KPIs for this BUC are listed in Table 6-20.

Table 6-20 – KPI definition – BUC 08

KPI number	KPI name	Target value
BG-BUC08.01	Number of detected critical outages (N-2) [#]	> 0
BG-BUC08.02	Percentage of considered congestions (N-2) [%]	100%

The first KPI that was relevant for this BUC was the number of detected critical outages, with the target value for it set to anything higher than zero. As four potential critical outages were detected, with five overloads coming as the consequences of them, it is clear that the goal defined by this KPI was fulfilled. The second KPI stated here was the one related to the assessment of every spotted overload and to the attempt of finding the appropriate corrective action for it. It was also stated in the BUC description that, if there are no corrective actions found, a change in the maintenance plan could be proposed. In this situation, however, the appropriate corrective actions were found for all five overloads in the grid (without the need to change the maintenance plan). This meant that the second KPI for this BUC also reached its set target value of 100%, and that the BUC 08 could be marked as successfully completed.

6.9 BUC 09 - Results

Once the complete methodology in which the TSO could use the developed solution for the checks of reliability of the transmission grid's operation, it was time to shift the focus from energy transmission to energy distribution and to concentrate on the BUC that is entirely dedicated to DSO. As a reminder, in this BUC, DSO spots an issue related to the overload of one of the lines in the grid and attempts to resolve it by utilizing the flexibility service providers connected to the distribution system. For that to be achieved, simulations needed to be done on the MV DT for the first time. This DT, for the purpose of illustrating the novel opportunities that the created solution provides to the DSO, consisted of the equivalent of the distribution grid supplied from one TSO-to-DSO substation. The original idea was to explicitly include all of the feeders going from that substation, but this was simplified since distribution grid typically consists of the radial feeders, so their mutual impact in the normal operation should not be considered. In addition to this, showing all feeders on a single diagram could harm the visibility of the actual issue and the way in which the proposed action helps in resolving it, negatively impacting the comprehensiveness of this report. Since the goal here is to illustrate the potential that ANN-based forecasts and their import into grid models give to the SO, it was estimated that this can successfully be done on the model with just one feeder, making it easier for the reader to focus on the key aspects of the task and to comprehend the obtained results efficiently. On the modelled feeder, there were:

- regular load, connected to the node 1101 – part available for demand-side response (DSR);
- regular load, connected to the node 1099 – part available for demand-side response (DSR);
- windfarm with battery storage attached, connected to the node 1099 as well (in the diagrams, aggregated to "Windfarm on DSO");
- electric vehicle charging station, connected to the node 1098 (also equipped for DSR);
- standalone battery storage, connected to the node 1100.

Table 6-21 – FSP state – DSO grid – problem no. 1

Facility	Operation power [MW]
Demand (1101)	-30
Demand (1099)	-15
Windfarm on DSO	0
EV station	-5
Battery storage	0

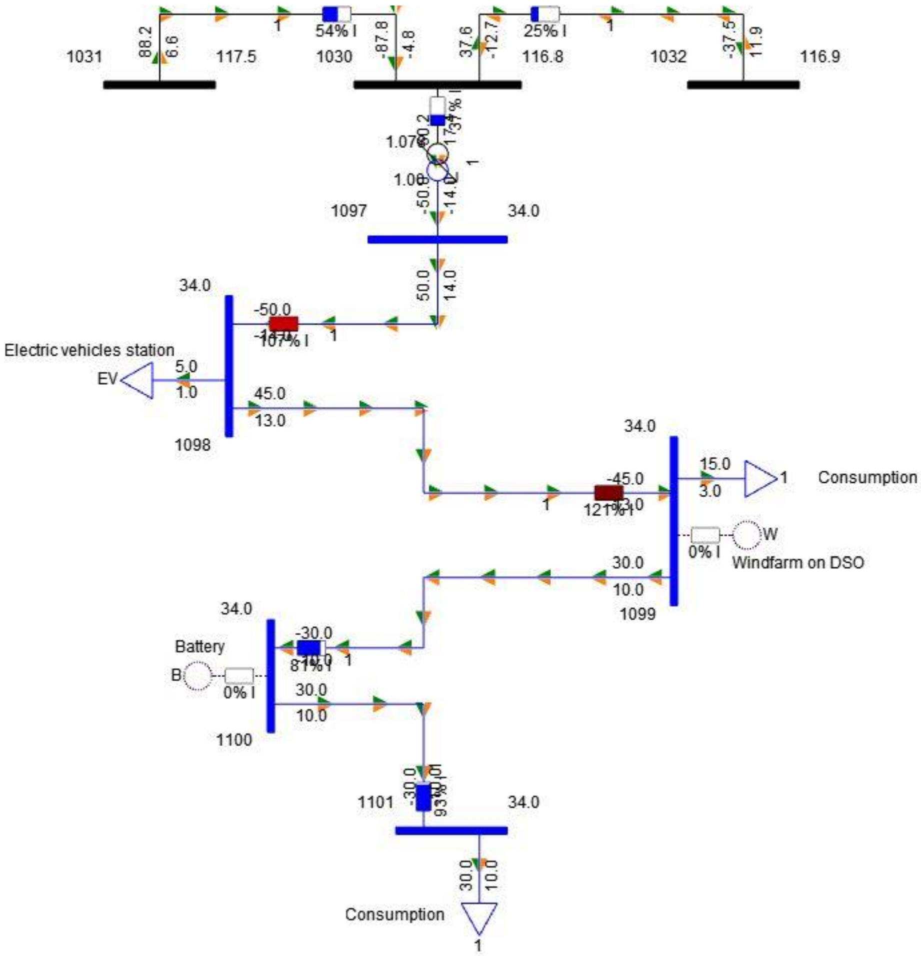


Figure 6-32 – DSO grid – problem no. 1

The configuration of these can be seen in Figure 6-32 and the following diagrams. This model was implemented in the PSS/E tool (with the production of wind farm scaled in line with the ANN-based forecasts for selected hours), after which the load flow calculations were run. One situation in which the issues were spotted can be seen in the Figure 6-32, where the main issue arises from the fact that battery storage attached to the wind farm actually charges from its production, causing issues with supplying all of the demand in this part of the grid without the WPP support and to the overloads of two lines. Powers of all of the connected facilities in this hour are also shown in the Table 6-21, where the positive values mean the production of energy, whereas the negative values mark withdrawing energy from distribution grid.

Table 6-22 – FSP state – DSO grid – solution no. 1

Facility	Operation power [MW]
Demand (1101)	-30
Demand (1099)	-15
Windfarm on DSO	10
EV station	-5
Battery storage	0

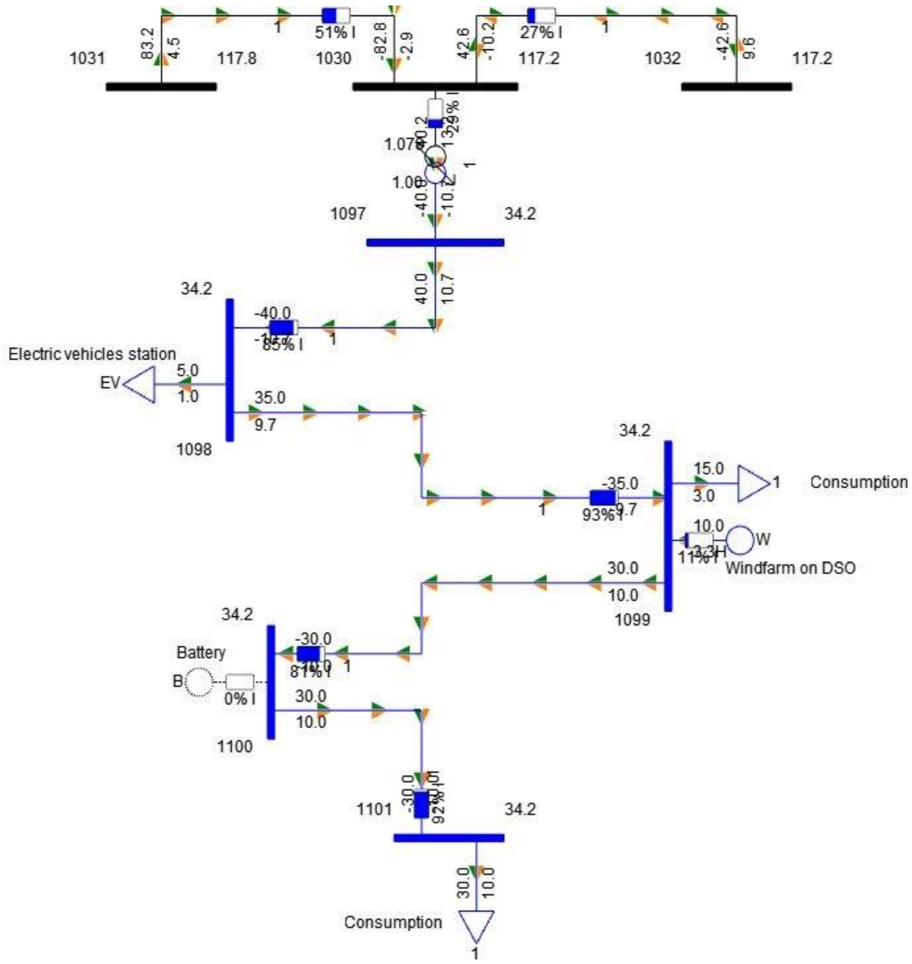


Figure 6-33 – DSO grid – solution no. 1

It is clear that, in this case, lines from node 1097 to node 1098, and from node 1098 to node 1099 got overloaded. Out of the flexibility service providers at its disposal, DSO could decide to reduce charging power of the battery next to the WPP, so some power for this part of the grid actually comes from it. This can be easily seen by comparing the values from the Table 6-21 with the ones from the Table 6-22, where the situation after the corrective action is presented. As it is also illustrated in Figure 6-33, the proposed corrective action would resolve the issues regarding overloads in the system efficiently.

Table 6-23 – FSP state – DSO grid – problem no. 2

Facility	Operation power [MW]
Demand (1101)	-5
Demand (1099)	-3
Windfarm on DSO	50
EV station	0
Battery storage	0

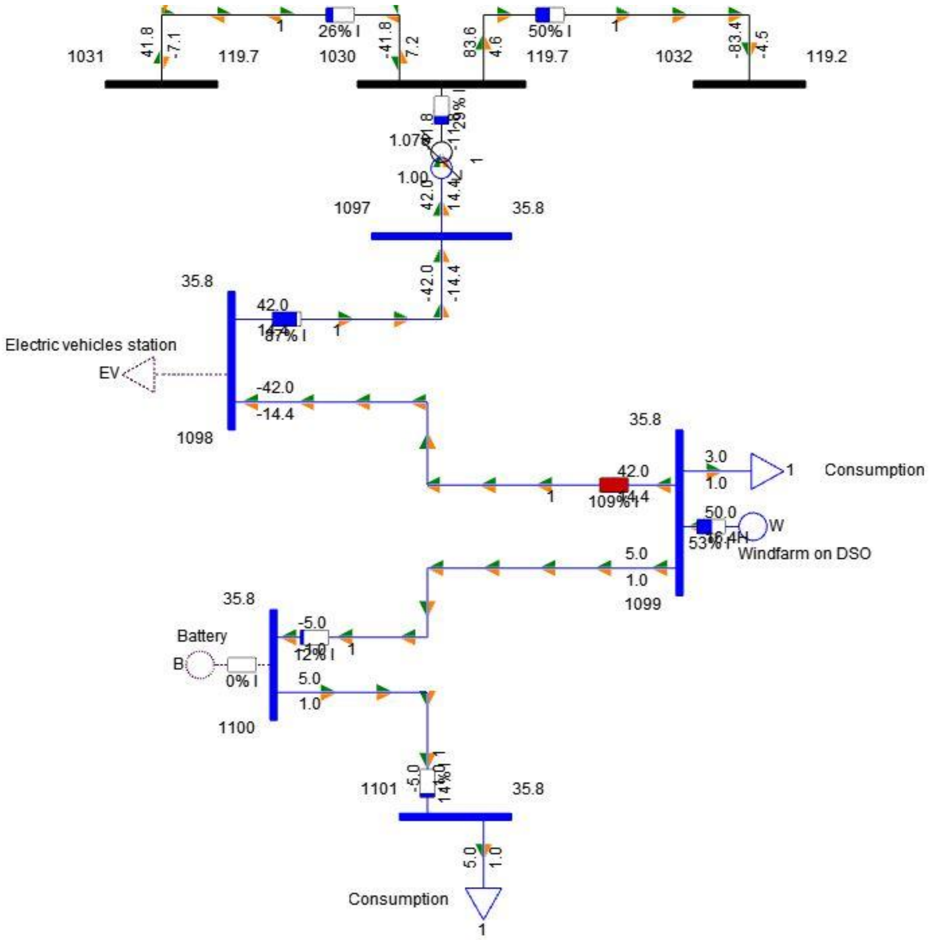


Figure 6-34 – DSO grid – problem no. 2

The reasoning behind this measure was that, if the issue is caused by the need to supply the demand, the easiest way to solve it would be to provide the demand with the additional source of power. Once that was done, the loadings of the lines in the grid fell below the maximal permitted limit. In another situation, the DSO could spot that the overload actually comes from the fact that, together with the production of the WPP, the battery accompanying it discharges with maximal power, overloading the line from that bus towards the transmission grid. This situation is shown in the table and figure below.

Table 6-24 – FSP state – DSO grid – solution no. 2

Facility	Operation power [MW]
Demand (1101)	-5
Demand (1099)	-3
Windfarm on DSO	50
EV station	0
Battery storage	-5

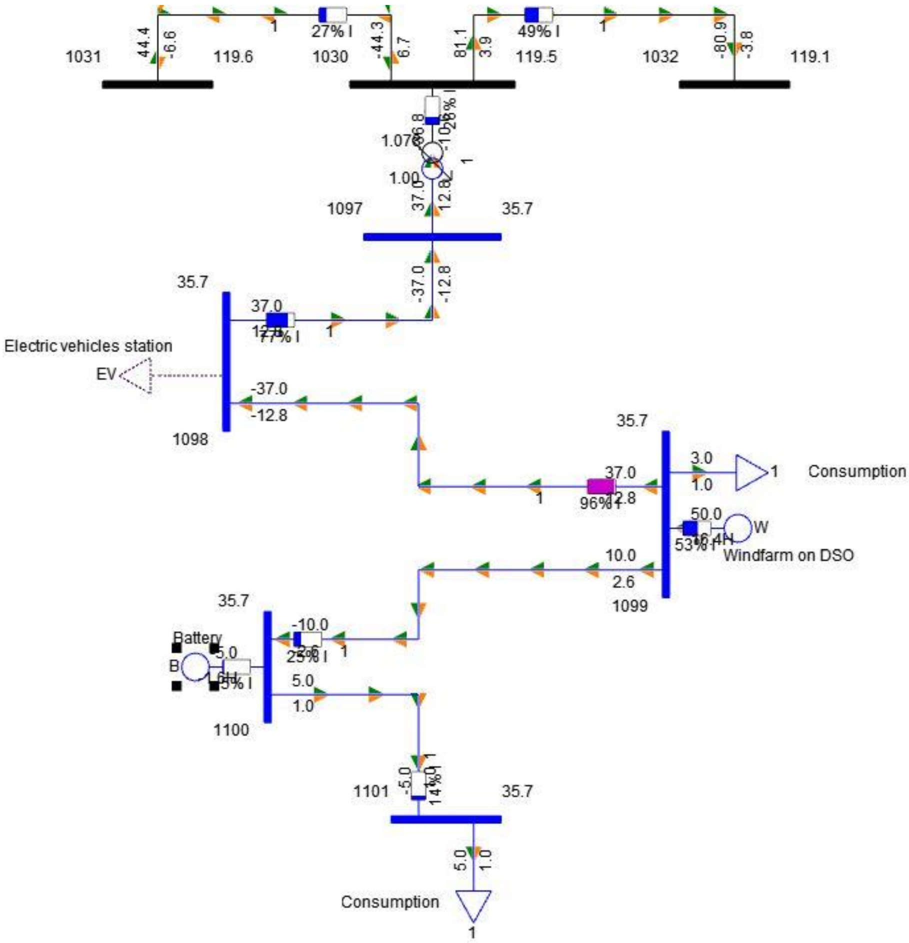


Figure 6-35 – DSO grid – solution no. 2

It is obvious that this problem has the opposite cause compared to the one illustrated in the previous case. In that situation, the issue was caused by the need to transfer energy down the feeder in order to supply the demand. Here, the issue stems from the need to evacuate the energy up the feeder and towards the transmission grid. In this situation, DSO could again change the mode of the battery next to WPP and solve the problem. However, it could also resolve it by activating the standalone battery storage that is located downstream from the WPP. The latter solution and the way it could affect the grid are shown below, in Table 6-24 (with the FSP states) and in the diagram provided in Figure 6-35.

It is worth mentioning that two different hours were used for case no. 1 and case no. 2 shown above, leading to the values of various demands differing from one another in two cases. This was only done to showcase the possibilities that the DSO could have in resolving the problems in advance. As having these kinds of forecasts, together with the plans of the flexibility service providers, could give the DSO time to react, they could reach out to the appropriate FSPs, collect the bids and run the calculations to check what would be the solution that would be the best. KPI for this BUC is shown in Table 6-25.

Table 6-25 – KPI definition – BUC 09

KPI number	KPI name	Target value
BG-BUC09.01	DSO-to-DSO mitigated congestions [%]	100%

This BUC only had one KPI attached to it, with it being the percentage of the congestions solved in the distribution grid by activating the flexibility service providers that are connected to distribution grid. There were two potential issues related to the overloads which were analysed, and both of them were resolved by activating the services of FSPs on distribution level. Hence, it is clear that this KPI has hit its 100% target. It should also be stated that the proposed actions weren't only ones that would solve the problems. Number of potential solutions would depend on each individual case, with the ANN-based forecasts giving experienced DSO employees the possibility to properly pick the optimal action.

6.10 BUC 10 - Results

In continuation of the previous BUC, BUC 10 was envisaged as a way to evaluate if the impact of the flexibility service providers connected to distribution grid can extend beyond the distribution system. For this evaluation to be conducted properly, the problem had to be simulated in transmission system, with the attempts to resolve it focusing on the FSPs connected on the distribution voltage level. In this step, it was also necessary to specify if the communication between the TSO and the FSPs that are not connected to its grid would be direct or there would be DSO in between those two. In this BUC, it was assumed that the communication would utilize DSO as an intermediator, in line with the Figure 6-36.

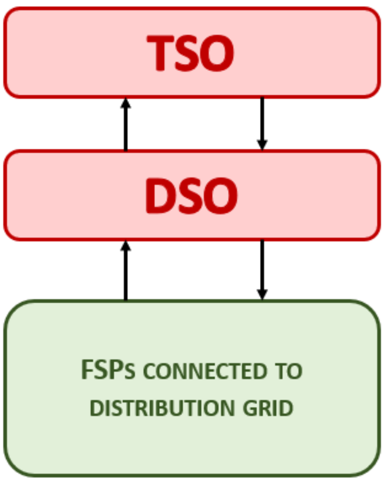


Figure 6-36 – Communication between TSO and FSPs on DSO level

In this situation, TSO would reach out to DSO with the request for the flexibility services, with the DSO collecting the bids of the FSPs and forwarding those to the TSO. The TSO would then pick the bids to be activated and forward this information to the DSO, which would then inform the chosen FSPs. The situation that was analysed here included the overload of the 110 kV line 1030-1031 in transmission grid, which had to be resolved by the FSPs on the DSO level. The operational powers of those FSPs in the initial state in which the issue was seen are provided in the Table 6-26. In the continuation of this, the single-line diagram in which the flows in the part of the grid of interest can be spotted is shown in the Figure 6-37. From it, it can be seen that the loading of the line 1030-1031 in the observed regime is equal to 116%, with the active power flow direction being from node 1031 and towards node 1030.

Table 6-26 – DSO FSP state – problem in TSO grid (for DSO FSPs to solve)

Facility	Operation power [MW]
Demand (1101)	-30
Demand (1099)	-8
Windfarm on DSO	0
EV station	-5
Battery storage	0

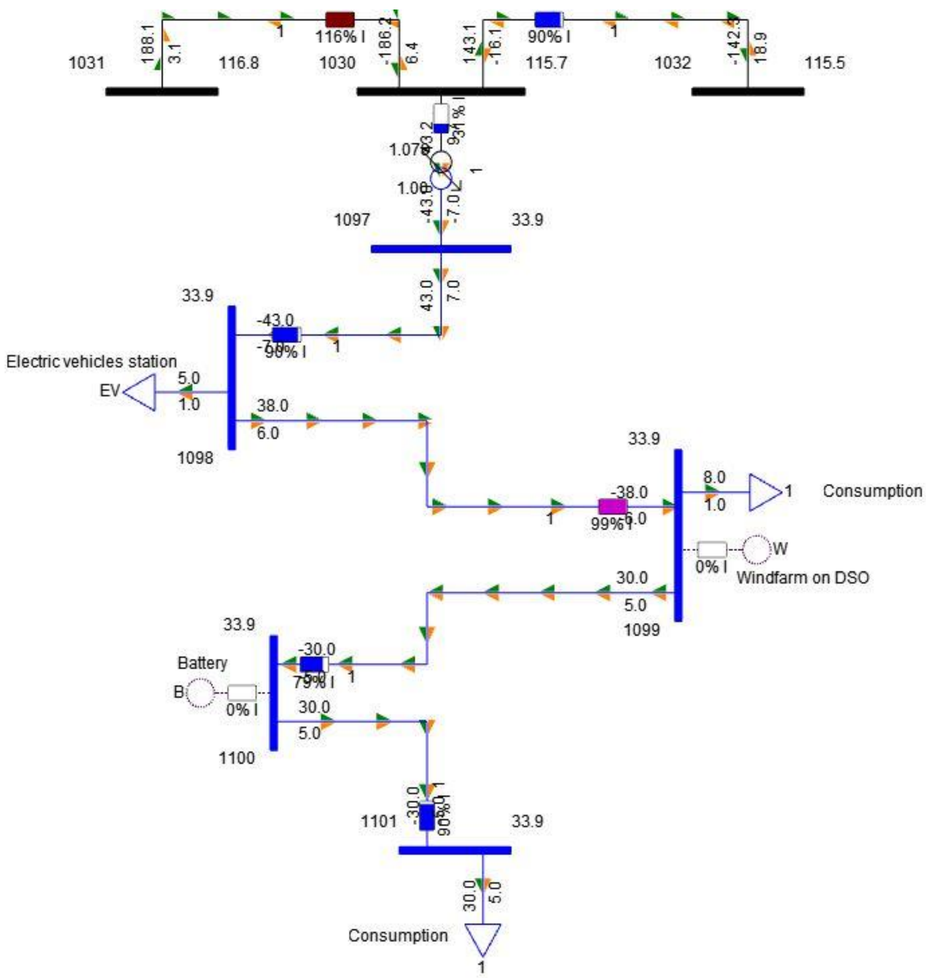


Figure 6-37 – TSO grid – problem (for DSO FSPs to solve)

For this BUC, the same connection between the EHV-HV DT and MV DT was utilized, with the potential FSPs in the distribution grid staying the same as they were in BUC 09. Hence, it was assumed that the TSO could count on the demand-side response from three loads, wind farm with the battery storage attached (wind farm production was scaled to be aligned with ANN-based forecast valid for selected hour), and a standalone battery storage. One of the possible solutions for this overload of 110 kV line between nodes 1030 and 1031 is presented below, in the form of the Table 6-27 and the Figure 6-38.

Table 6-27 – DSO FSP state – problem in TSO grid solved by DSO FSPs

Facility	Operation power [MW]
Demand (1101)	-20
Demand (1099)	-5
Windfarm on DSO	20
EV station	-3
Battery storage	5

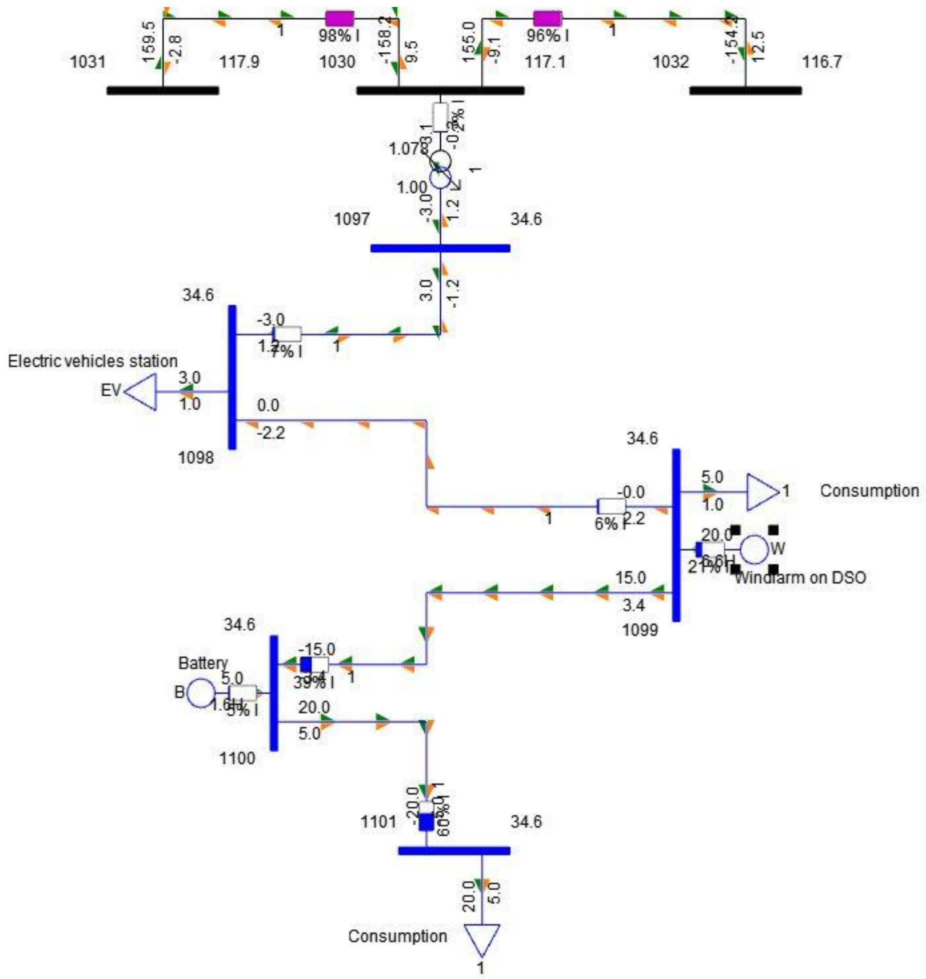


Figure 6-38 – TSO grid – problem solved by DSO FSPs

The solution shown here envelops the activation of all of the available resources, with the DSR getting activated on all three loads, standalone battery being switched on, and power of charging the battery attached to the WPP getting reduced. As it was stated, this was only one of the potential solutions, so the TSO would need to (based on the actual collected offers) evaluate the possibilities at its disposal properly in order to actually select the best option out of the ones offered to it. However, it is shown here how the existence of combined EHV-HV and MV DTs, accompanied by the ANN-based auxiliary DTs, could provide TSO with the tool needed for this estimation. KPI for this BUC is given in the table.

Table 6-28 – KPI definition – BUC 10

KPI number	KPI name	Target value
BG-BUC10.01	DSO-to-TSO mitigated congestions [%]	100%

If one would look at the assumptions and conclusions of the analyses done within the part of the work connected to this BUC, they could conclude that there was one overload in the TSO grid (on the OHL from the node 1030 do the node 1031), and that it was indeed resolved by the activation of the FSPs on the distribution voltage level. Thus, the value of this KPI is equal to its target value of 100%, making BUC 10 successfully completed. This was also the last BUC defined in the scope of the Bulgarian pilot.

6.11 SUC 01 - Results

As the outcomes of all BUCs that were defined for the Bulgarian pilot are now fully presented, it is time to move on to the SUCs defined within this pilot. These SUCs, as was described in the Chapter 4, deal with the particular parts of the processes that were not explicitly drawn attention to in the BUCs, but should, in the opinion of the partners, have some share of the spotlight. The first of those is the SUC that considered the situation in which the system operator (in this case, the TSO), receives the ANN-based forecasts and runs the developed R and Python scripts to input those forecasts into the models. When that gets completed, the employee running these scripts would also need to perform load-flow calculations on the models in order to check if there are any issues in the base state of the grid. It can be concluded that this is something that has already been all but confirmed in the BUCs 06-10, hence testifying that not all of the SUCs were done after the BUCs were completed, with some of them being the interim steps between the various BUCs. The chronological order of the UCs of Bulgarian pilot was that, first, the BUCs 01-04 were completed, being the needed precondition for all the other UCs. After that, BUC 05 and SUC 01 were done, utilizing the outcomes of BUCs 01-04 directly. Next, BUCs 07 and 08 were completed, along with the SUCs 02 and 03. When this was finalized, BUCs 09 and 10, as well as the SUC 04, could be completed. In the very end, BUC 06, dealing with a task of its own, was done.

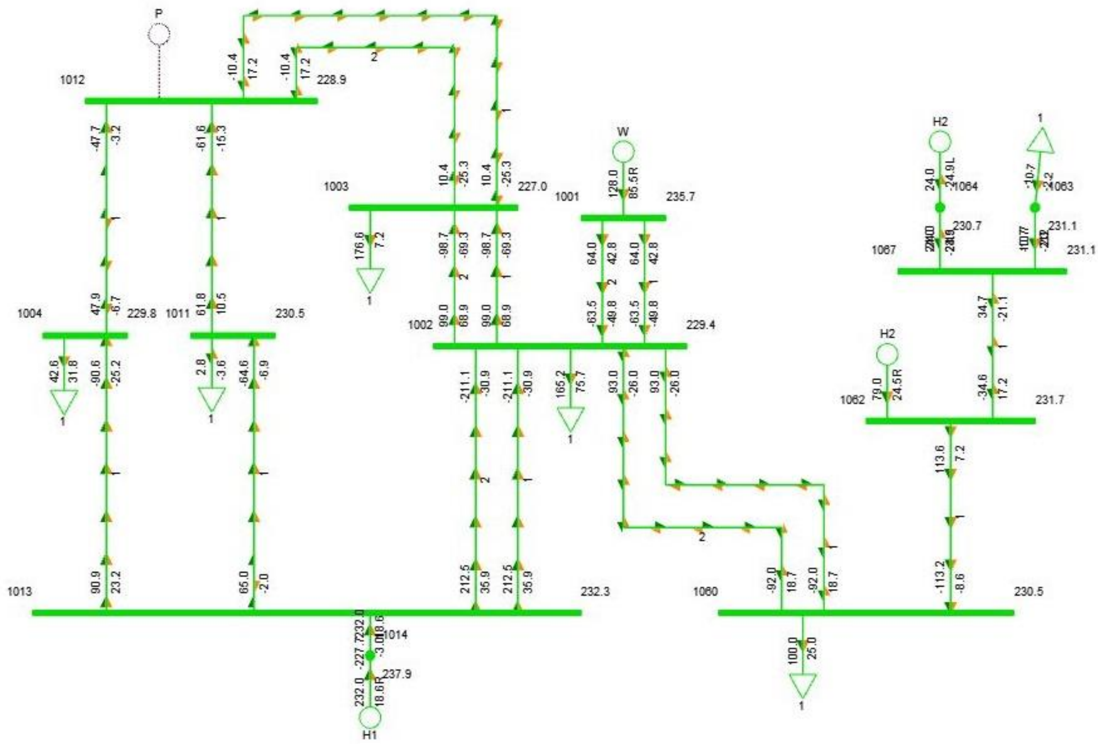


Figure 6-39 – TSO grid – example of the load flow (no loadings)

Even though this SUC has not been listed as a precondition on the BUCs 06-10, that is purely due to it being defined after the BUCs were completed. In practice, its successful completion was indeed seen as a precondition for all of those, because, without the proper implementation of ANN-based forecasts in models, none of the later UCs would make any sense, nor would it demonstrate any improvement. In order to show the results of the load flow analyses, a diagram similar to the ones included in some of the BUCs was created and enclosed here. The numerical values of the flows are also provided there.

Of course, this diagram shows only the part of the transmission grid of Bulgaria, as showing the entire system would take too much space in this report. What is clear, however, is that the analysis has been performed successfully and that the results were available after that. PSS/E, as already demonstrated, also has the possibility of directly showing the percentual loading of the lines and transformers in the diagrams. Such a diagram (with the percentual loadings included) is enclosed here as the Figure 6-40.

From looking at this, it would be clear to the employee of the system operator that no overloads would be expected in the base case of the grid. However, there are some lines that have the flows exceeding 50% of their percentual loads, so N-1 analysis could indicate some issues there. As the forecasts have been done for 72 hours in advance, this diagram shows one of them (different from the one selected for BUCs 07 and 08), but illustrates the possibilities that would be given to the TSO if solutions which are proposed in the pilot would become standard practice. KPI defined for this SUC is shown in Table 6-29.

Table 6-29 – KPI definition – SUC 01

KPI number	KPI name	Target value
BG-SUC01.01	Successfully conducted load flow analyses [#]	> 0

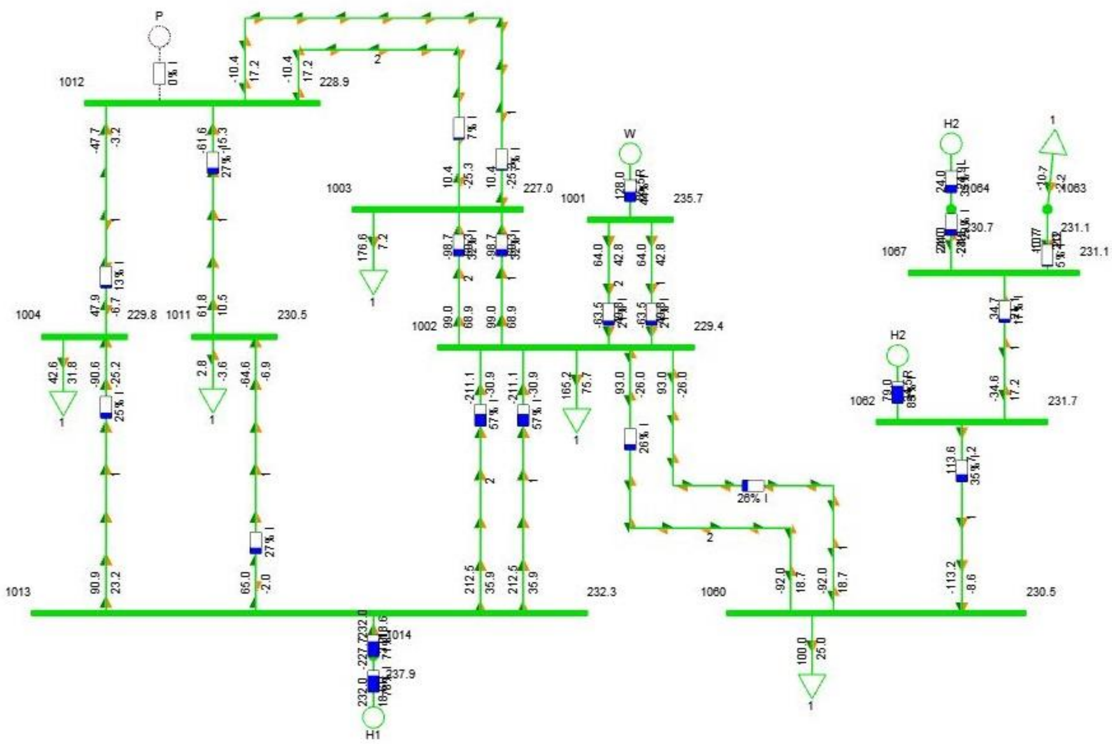


Figure 6-40 – TSO grid – example of the load flow (with loadings)

Even without this elaboration, the previous subchapters have already shown that the calculations such as the one listed in the KPI were done a lot of times in the scope of the Bulgarian pilot's work. Insisting on the fact that this has been done for 72 different hours, with the ANN-based forecasts considered for each of them, only strengthens that conclusion. As the number of the performed analyses exceeds the set value of zero, it is clear that the goal defined in this SUC has been achieved and that the SUC could be completed without any issues or problems related to the scripts or running the assessments.

6.12 SUC 02 - Results

This SUC was the one focusing on the additional options that the DSO would have if the forecasts done by the ANNs were paired with the models. In line with that, the situation that has been envisaged here in which the DSO gets the forecasts of relevant system parameters and runs the calculations in order to estimate energy exchange between itself and TSO through one of the substations connecting them. Previously, this would mean estimation of the power with which the distribution system takes energy from transmission grid. However, the introduction of energy storages and renewable energy sources connected to distribution grid means that not only there is now an option that the exchange between the distribution and transmission system in some regimes becomes close to zero, but that there is also a chance that the energy would flow from the distribution grid to transmission grid. To illustrate this, MV DT was used again. On it, the forecasts (here, only the forecasts of WPP productions were relevant as there were no SPPs or OHLs that underwent ampacity forecasts in this part of the distribution grid) were implemented and load-flow calculations were run for each of the 72 hours included in forecasts. It should be clarified that the WPP forecast was the same as for the WPP Sveti Nikola, but scaled down from the power of that WPP to the power appropriate for the distribution level. This part of the grid, with the power flows in it shown for one of the 72 hours, can be seen in the diagram provided below.

From Figure 6-41 it is visible that, in this hour, power of energy exchange between the TSO and DSO was equal to 13 MW and that the energy went from the transmission grid towards the distribution grid. Same calculations were then performed for all 72 included in the period relevant for the forecasts, with the inter-SO exchanges getting noted, which was also done by a script written for this purpose. These exchanges were then used to create a line diagram shown in the figure, in which positive values mean energy flow from transmission grid to distribution grid, and vice versa.

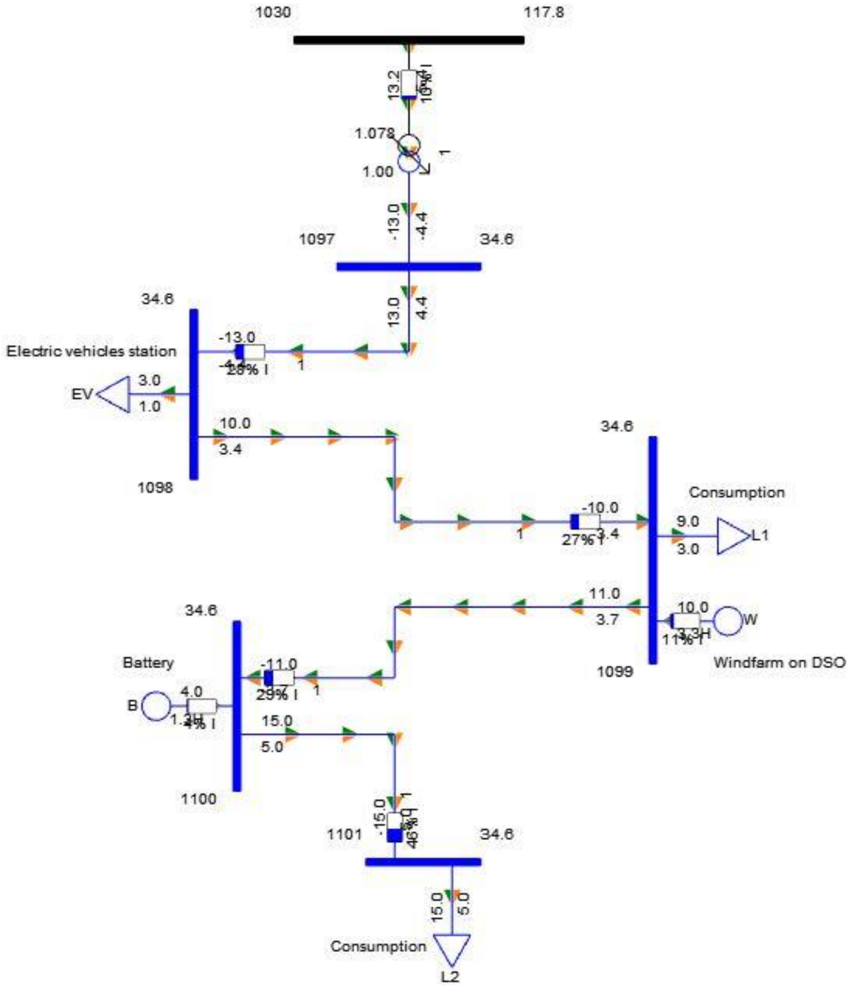


Figure 6-41 – Inter-SO energy exchange – load flow

In addition to the designation of positive and negative values explained above, in Figure 6-42 colour coding was also applied in this diagram to make it even more comprehensible for the readers. It was decided to use red colour for the maximal values of the energy exchange from TSO grid to DSO grid, blue colour for the maximal energy exchange from DSO grid to TSO grid, and different shades between those two for the values in-between. It is clear that, for the observed period, energy went from the transmission grid towards the distribution grid in the majority of hours. However, there are some hours (especially during the night hours in which the load in the distribution grid is low and production of WPP high) in which energy changes direction and actually goes into the transmission grid from the distribution grid. For this SUC, one KPI that was related to energy exchanges was defined, as shown in the Table 6-30.

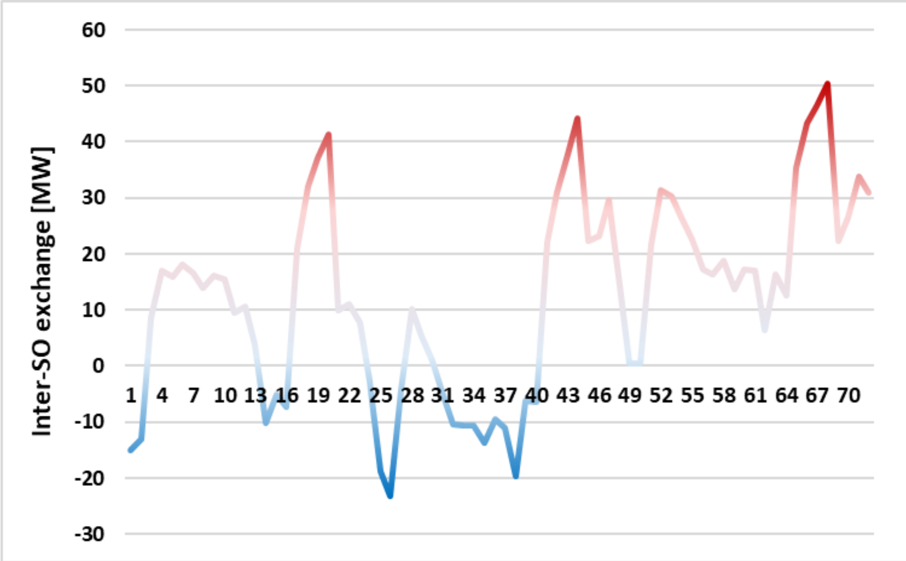


Figure 6-42 – Inter-SO energy exchange – 72 hours

Table 6-30 – KPI definition – SUC 02

KPI number	KPI name	Target value
BG-SUC02.01	Successfully estimated energy exchanges [#]	> 0

The entre point of this SUC was to demonstrate the possibility of utilizing both MV DT and EHV-HV DT for the estimation of the energy exchange between the SOs. This is somewhat related to the BUC 10, in which the possibility for the energy exchange was utilized as a mean of flexibility exchange among the SOs. In line with that, the KPI was set to having at least some successfully completed estimations of the energy exchanges between the TSO and the DSO in the designated point. As this was performed for all 72 hours that were enveloped by the forecasting period, it is safe to say that the KPI has reached (and exceeded by a large margin) the target value, making SUC 02 of the pilot successfully completed.

6.13 SUC 03 - Results

Second-to-last SUC of the Bulgarian pilot was the one in which the effects of the ANN-based ampacity forecasts on the situation in the system and the avoidance of the false alarms that could otherwise be raised without the practical need for that. These alarms are mostly related to the situations in which the TSO would use the grid models at its disposal to run the load flow calculation and N-1 assessment, after which the potential detected overloads would be highlighted. Once those get spotted, resources would be dedicated to picking the optimal remedial actions that would be necessary to mitigate those problems. If the same issue persists for some time, there could even be some planning measures (such as the construction of new lines or the reconstructions of the existing infrastructure) getting foreseen in order to permanently resolve the overload. However, in some of the situations, the overloads might not be related to the actual flows putting the line at risk from any aspect. In those cases, the problems would be signalled strictly due to the conservative approach that utilizes the static OHL ratings. Hence, planning any kind of activities based on those would be the sub-optimal utilization of the resources at disposal, especially if the measures are the ones related to the system development, where the budget given to the TSO would also be on the line. This could be avoided by utilizing the ANN-based forecasts.

Of course, that is not to say that all of the problems related to the overloads in the grid could be solved by the application of the ratings based on the actual climatic conditions, but that there is definitely a potential for that. For the potential to be examined, created EHV-HV DT was taken and the calculations were done for all of the 72 hours included in the forecasting period. Here, both the load flow analyses and the N-1 assessments were run for two situations – for the situation in which the ratings of the 400 kV OHL SS Blagoevgrad – SS Thessaloniki and 220 kV OHL SS Plovdiv – SS Aleko were static and for the situation in which these ratings were adjusted according to the forecasts. The forecasts and the static ratings can actually be found in the diagrams shown in Subchapters 6.4 and 6.5. Percentual loading of the 400 kV interconnection between Bulgaria and Greece for both of these cases, in the base state of the grid, can be found in the diagram below. If one would compare this diagram to the one shown in the subchapter dealing with the BUC 05, it would become clear that the periods when the percentual loading is higher with the static ratings match the periods in which there is a potential for the increase of the line rating by taking into account the climatic conditions and the potential for the line cooling.

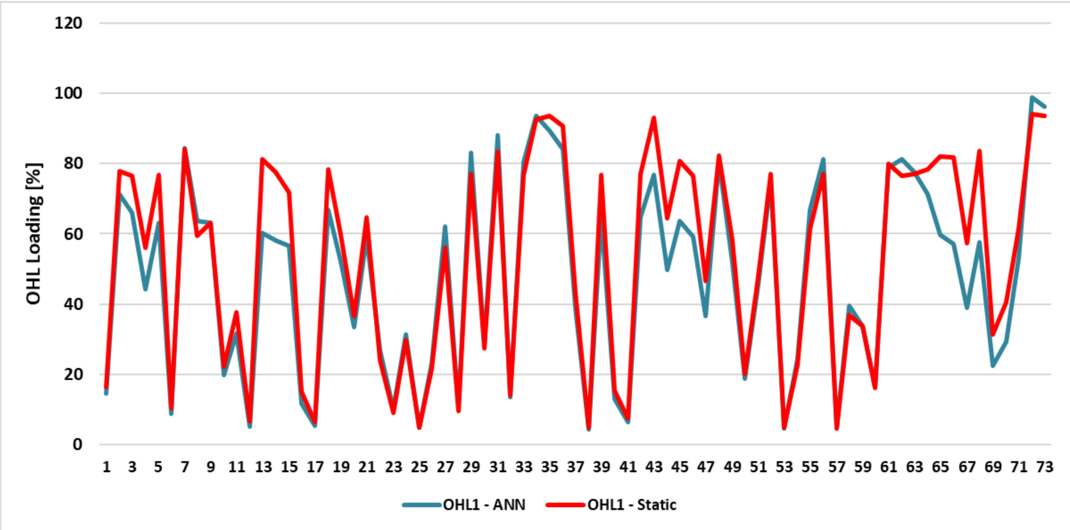


Figure 6-43 – Loading comparison – 400 kV interconnector line

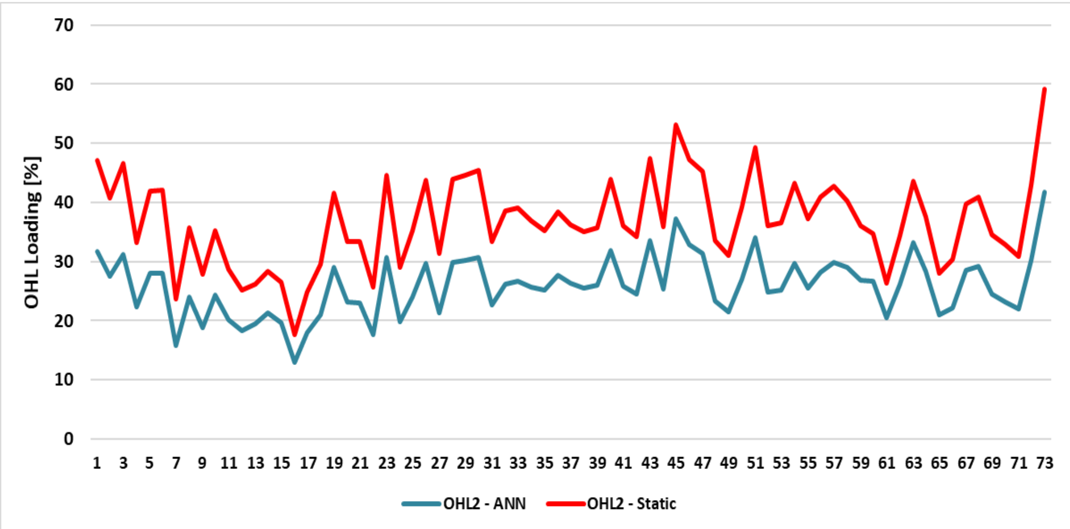


Figure 6-44 – Loading comparison – 220 kV internal line

It is also clear that there are hours in which the percentual loading of the line is higher when the ANN-based forecasts are applied. As explained in the Subchapter 6.5, these are the hours in which the usage of the ANN could actually improve the reliability of the grid, since, in them, static rating is higher than the forecasted one. Similar diagram with a comparative assessment can be found in the figure below, but, this time, the focus was on the 220 kV OHL between SS Plovdiv and SS Aleko and its loading in the 72 hours. The conclusions that could be listed for the previous line can also be reached for this OHL.

This line actually showed the results even better than the ones obtained for the interconnection, but it is visible that both of them have significant potential for the ampacity forecasts' application. Along with showcasing the differences between the line loadings in cases in which the static ratings and the ANN-forecasted ratings are used, another goal of this SUC was to address those differences and to try to explain their causes. By observing the line ratings and the climate conditions in the same hours, the reasons behind the variations of the ratings could be determined, with the wind speed and direction, as well as the outside temperature, being the factors with the highest impact. Namely, in those hours in which the outside temperature was lower and wind speed was higher, the difference between the two ratings (and, in turn, between the percentual loadings of the lines) was way more prominent. On the contrary, in the hours in which the wind speed was close to zero, the spotted difference between the two ratings also fell to rather small values. KPI that has been defined for this SUC is listed below.

Table 6-31 – KPI definition – SUC 03

KPI number	KPI name	Target value
BG-SUC03.01	Percentage of assessed differences [%]	100%

The term "assessed differences" was here related to the differences in the percentual loadings of the lines for which the explanation was provided. Since above this table there is an elaboration that describes the mutual relation between the selected climatic conditions and the line ratings (and the percentual loading of those lines as well), it can be stated that the explanation for the detected differences was indeed provided. Hence, it can also be concluded that the rating variations were thus explained, that this KPI in turn did reach its target value of 100%, and that this SUC was also successfully completed.

6.14 SUC 04 - Results

Building even further upon the foundation set by BUC 09 and BUC 10, SUC 04 went both into the FSPs' activation in order to resolve the issue in the same grid to which they are connected (in line with how BUC 09 investigated the possibility to solve the problem in the distribution grid by activating the FSPs that are also located at the distribution voltage level) and into the possibilities of flexibility exchange among the SOs (following how, in the BUC 10, issues in the TSO grid were mitigated by activating the FSPs connected to the distribution grid). Here, the way of communicating between the TSO and FSPs, illustrated in diagram within the BUC 10 subchapter, needed to be extended slightly, as given below.

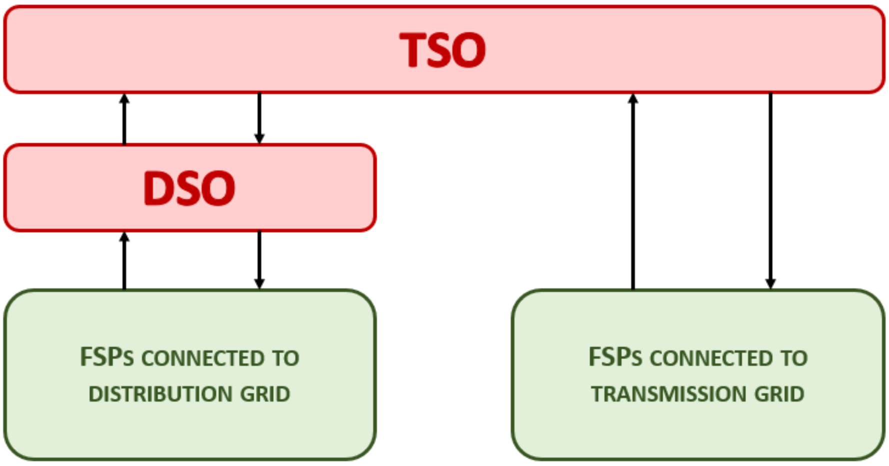


Figure 6-45 – Communication between TSO and FSPs (general)

To evaluate this combined impact of the FSPs, regardless of their voltage level, same merging of the EHV-HV DT and MV DT as in the BUC 10 was conducted. The issue was once again seen on the 110 kV line between nodes 1030 and 1031. The difference from the BUC 10 is that, as shown in the diagram given in the Figure 6-46, it was also presumed that there was a standalone battery storage connected to the TSO grid on top of all of the FSPs that are connected to the DSO grid in this region. The state of these FSPs (both the ones on the DSO level and the battery on the TSO level) in the state of the system in which the overload of line 1030-1031 amounting to 116% occurs can be seen below, in Table 6-32. Again, positive and negative values mark the energy production and the energy demand, respectively.

Table 6-32 – FSP state – problem in TSO grid (for all FSPs to solve)

Facility	Operation power [MW]
Demand (1101)	-30
Demand (1099)	-8
Windfarm on DSO	0
EV station	-5
Battery (DSO)	0
Battery (TSO)	0

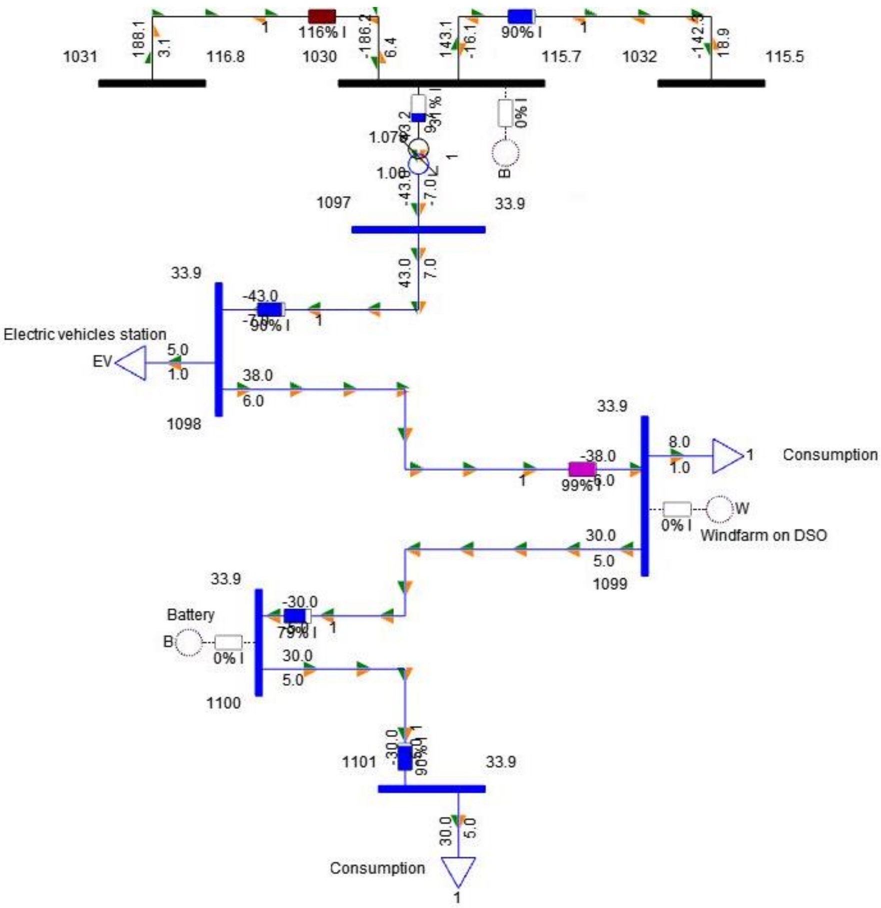


Figure 6-46 – TSO grid – problem (for all FSPs to solve)

The situation that was simulated here was the one in which the TSO spots a potential issue in the grid in advance and seeks the bids from the FSPs that could help in mitigating that issue (TSO would request the bids directly from the FSPs connected to its grid, while this request would need to go via DSO for the FSPs connected on the distribution level). Once the bids are collected, TSO could run the analyses on the created merged DT in order to pick the right combination of available services, taking all of the relevant factors into consideration. One of the potential solutions for this problem is enclosed below.

Table 6-33 – FSP state – problem in TSO grid (solved by all FSPs)

Facility	Operation power [MW]
Demand (1101)	-30
Demand (1099)	-8
Windfarm on DSO	0
EV station	-5
Battery (DSO)	5
Battery (TSO)	30

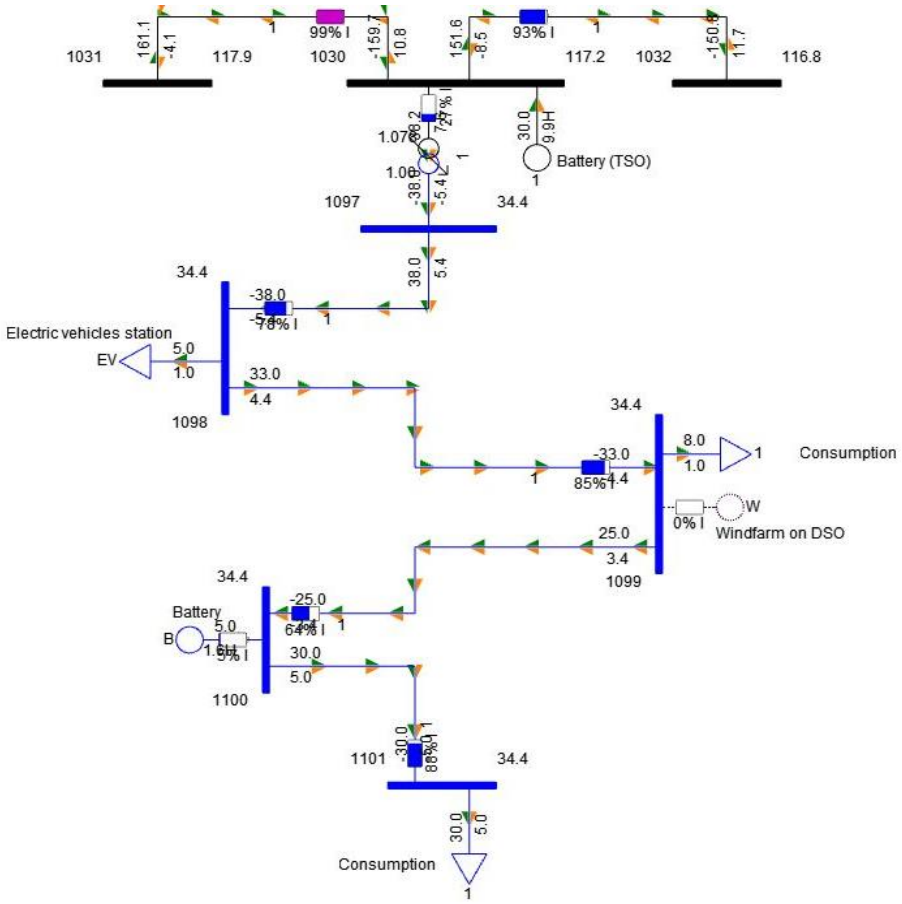


Figure 6-47 – TSO grid – problem solved by all FSPs

Albeit it was stated before this figure that the shown solution was only one of the potential solutions, it should be highlighted that it can just as well be the optimal one, since it required only two FSPs to be activated simultaneously. Those were the two included standalone battery energy storage systems, one being on the TSO level and the other being on the DSO level. By activating these, the issue in the transmission grid was indeed resolved and the loading of the problematic line fell below the permitted loading in the selected hour. Related to this, the KPI defined for this SUC is provided in the Table 6-34.

Table 6-34 – KPI definition – SUC 04

KPI number	KPI name	Target value
BG-SUC04.01	All-to-TSO mitigated congestions [%]	100%

Similar to the logic used in BUC 09 and BUC 10, here it can also be stated that there was one problem in the transmission grid that was detected in the analysis. It is also clear that it was successfully solved (in the designated simulation environment) by the combination of the FSPs connected both to the TSO and to the DSO grid. In accordance with it, it can be concluded that this KPI also managed to reach the target value of 100%. Hence, it can be stated that final SUC of the Bulgarian pilot has also been done successfully. Not only that, but, since this was also the final UC of the entire pilot, this also marked the successful completion of all of the calculations that were foreseen by the scope of Bulgarian pilot. The remaining steps of the pilot in the TwinEU project will be explained in the final chapter of this report.

7 Conclusions and Next Steps

Once all of the results obtained within Bulgarian pilot were presented, the only thing that remained was to use those results in order to create a summary of the main conclusions and to estimate whether the major targets of the pilot were actually achieved or not. These conclusions are listed below:

- The successful development of the DTs and the scripts for the data exchange among the DTs proved that this technology can be implemented without issues in the day-to-day work of the SOs, aided by the fact that compatibility of DTs with the existing tools was one of the priorities.
- The high fidelity of data exchange and automatic development of the hourly DTs reduces the possibility of errors in information input that could arise in case all of these tasks would need to be done manually, thus increasing the reliability of the performed assessments further.
- ANN-based forecasts of all chosen system parameters (WPP production, SPP production, OHL ampacities) were done with very low error value, indicating high accuracy of these forecasts and verifying that their application could indeed be fruitful in the system operation tasks.
- As all of these forecasts (of course, once the ANN gets trained for the specific purpose, which can take some time) can be obtained in less than a minute for 72 hours in advance, it is clear that this implementation would be aligned with the timeframes used in the system operation.
- Regarding the utilization of the genetic algorithm for the optimization of the connection points for the renewable sources and storages, the results that were obtained and verified through the brute-force check proved the potential that this method could have for aiding in this task.
- The fact that all needed calculations and the whole optimization process itself took place in a matter of minutes also confirmed that the efficiency of the connection procedures wouldn't be harmed in any way (if anything, it could only be improved) if this method was implemented.
- Moreover, reliability of the algorithm was also verified as the same algorithm was run several times with the same input data and the results were the same (and correct) every time, hence highlighting the trustworthiness of the developed solution and outcomes obtained from it.
- Finally, the ways in which the SOs could profit in case the created solutions get widely applied were illustrated by using a large number of Use Cases, highlighting the contribution which the TwinEU project could have in the system operation (on all voltage level) in the years to come.

In the final year of the project, the results that have been presented here will be expanded upon, both in terms of further in-depth assessment of the possibilities that they could offer to the users and in terms of the practical steps which would need to be taken in to properly exploit these outcomes in everyday engineering practice. For the former, running additional assessments and forecasts (maybe performing the forecasts of some other system parameters, such as the load of the substations in the grid or establishing the relation between the flows on the lines and the relevant climate parameters) could be considered. For the latter, the business plan will need to be developed, along with the tests of the scalability of the developed solutions (in particular, scalability regarding the geographical scope to which the solution could be applied in order to verify if the solution could be scaled up even to EU level) that will potentially be conducted. All of these will serve as a further verification that outcomes of this pilot will be useful to the system operators (or some other users, such as external stakeholders and the academies), contributing to the fulfilment of the foreseen benefits of TwinEU in the process.