A novel smart grid architecture that facilitates high RES penetration through innovative markets towards efficient interaction between advanced electricity grid management and intelligent stakeholders

H2020-GA-863876

Pilot demonstration setup plan, experimentation plan and validation methodology

Deliverable D7.1

Document Information

Scheduled delivery	31.03.2021
Actual delivery	24.03.2021
Version	Final
Responsible Partner	AIT

Dissemination Level

PU Public

Contributors

Filip Pröstl Andrén (AIT), Maria-Iro Baka (UCY), Loizos Loizou (UCY), Christina Papadimitriou (UCY), George Georghiou (UCY), Hera Mansoor (BnNETZE), Thoma Malte (BnNETZE)

Internal Reviewers

Prodromos Makris (ICCS)

Copyright

Acknowledgements

The research leading to these results has received funding from the EC Framework Programme HORIZON2020/2014-2020 under grant agreement n° 863876.

Glossary of Acronyms

Project management terminology

Acronym	Definition
HLUC	High Level Use Case
WP	Work Package
UCS	Use Case Scenario

Technical terminology

Acronym	Definition
AC	Alternating Current
AFAT	Automated Flexibility Aggregation Toolkit
API	Application Programming Interface
ATP	Automated Trading Platform
BEMS	Building Energy Management Systems
BMS	Building Management System
BRP	Balance Responsible Party
CAPEX	Capital Expenditures
CES	Centralised Energy Storage
CHIL	Controller Hardware-In-the-Loop
CHP	Combined Heat and Power
DA	Day-Ahead
DAD	Day-Ahead Dispatch
DC	Direct Current
DER	Distributed Energy Resource
DES	Distributed Energy Storage
DLEM	Distribution Level Energy Market
DLFM	Distribution Level Flexibility Market
DN	Distribution Network
DND	Distribution Network Dispatch
DSO/TSO	Distribution/Transmission System Operator
DSM	Demand Side Management
ELM	Extreme Learning Machine
EM	Energy Market
ENC	Energy Centre
EPEX	European Power Exchange
ES	Energy Service
ESP	Energy Service Provider
ESS	Energy Storage System
EV	Electric Vehicle
EVSS	Engineering and Validation Support System
FMO	Flexibility Market Operator
FMCT	Flexibility Market Clearing Toolkit
FRT	Frequency Ride Through

FST	FlexSupplier’s Toolkit
HIL	Hardware-In-the-Loop
ICT	Information and Communication Technology
KPI	Key Performance Indicator
LMO	Local Market Operator
LV	Low Voltage
LVRT	Low Voltage Ride Through
MAE	Mean Absolute Error
MO	Market Operator
MTU	Market Time Unit
MV	Medium Voltage
OPEX	Operational Expenditures
OPF	Optimal Power Flow
PCC	Point of Common Coupling
PHIL	Power Hardware-In-the-Loop
PV	Photovoltaic
RES	Renewable Energy Sources
RI	Research Infrastructure
R/P/I-DLFM	Reactive/Proactive/Interactive Distribution Level Flexibility Market
RMSE	Root Mean Squared Error
RNN	Recurrent Neural Network
RM	Reserve Market
RT	Real-Time
SAI	System Adequacy Index
SCADA	Supervisory Control And Data Aquisition
S/W	Software
TN	Transmission Network
TLMP	Transmission Network Locational Marginal Price
TRL	Technology Readiness Level
VS	Validation Scenario
WM	Wholesale Market

Table of Contents

List of Figures and Tables

List of Figures

List of Tables

Document History

This deliverable includes the research output of task 7.1. It includes a detailed plan for the pilot demonstration setup and experimentations to validate the research outcomes of WPs 3-5 in a laboratory and real-life environment.

Table 1: Document History Summary

Revision Date	File version	Summary of Changes
12/01/2021	v0.1	Draft ToC circulated among all consortium partners
20/01/2021	v0.2	Final ToC version has been agreed and writing task delegations have been provided to all involved partners.
09/02/2021	v0.3	All partners contributed their 1st round inputs.
26/02/2021	v0.5	Internal WP7 revision (1st round of review comments).
05/03/2021	v0.7	All partners contributed their 2nd round inputs according to the 1st round of review comments.
12/03/2021	v0.8	Internal review process (2nd round of review comments).
19/03/2021	v0.9	Integration of review results
24/03/2021	Final	Coordinator (ICCS) made final enhancements/changes and submitted to ECAS portal

Executive Summary

This report is an official deliverable of H2020-GA-863876 FLEXGRID project describing the plan for the validation setup and experimentation together with the validation methodology, which will be used in Work Package (WP) 7 for validating the FLEXGRID methods. The goal of FLEXGRID is to provide unified services for different energy sector stakeholders, such as Distribution System Operators (DSO), Transmission System Operators (TSO), Energy Service Providers (ESP) and aggregators of Renewable Energy Sources (RES) and flexibility assets. The work in WP7 will contribute to this by providing a validation approach that will evaluate the FLEXGRID services from these stakeholders' point-of-view.

In order to validate the methods and tools developed in FLEXGRID, a validation methodology was defined based on the ERIGrid Holistic Validation Methodology [Bla16]. Three validation strands will be followed in WP7. The first strand focuses on validating aggregator services and will be carried out as pilot tests at UCY's campus grid at Technology Readiness Level (TRL) 5. It focuses on evaluating the FLEXGRID tools that can be used ESPs and aggregators for automated energy flexibility aggregation. For this strand, three validation scenarios were identified: optimal management of FlexRequests, optimal creation of FlexOffers, and an extended study using additional virtual FlexAssets.

The second strand focuses on FLEXGRID's services directed towards DSOs and how these can be optimally provided by ESPs. This strand will also be carried out as a pilot using bnNETZE's test system in and around the city of Freiburg, Germany at TRL 5. Four validation scenarios were identified, where the first three are focusing on the validation of different forecasting methods (Photovoltaic – PV, price, and load forecasts). In the fourth scenario, the forecasting methods will be used in a field trial to enable peak shaving of bnNETZE's entire distribution grid.

The third strand focuses on validating the Distribution Level Flexibility Market (DLFM) architectures proposed by the FLEXGRID project. Strand number three will be carried out as simulations and tests in AIT's SmartEST lab at TRL 4. Four validation scenarios were identified for this strand, where the first covers the setup and development of the simulation setup. Two validation scenarios cover the implementation and simulation of different x-DLFM architectures. The main validation scenario covers the evaluation of the DLFM architectures by simulating each architecture under different conditions.

The main outcome of this deliverable is the validation scenarios defined for each strand. These will be the main basis for the further activities of WP7. The next steps will be to specify detailed experiments based on the validation scenarios. In parallel, the test setups need to be further developed by integrating the FLEXGRID tools and methods. The last step in the validation methodology is to carry out the specified experiments and evaluate the results.

1 Introduction

1.1 Purpose of the document

The goal of FLEXGRID is to facilitate energy sector stakeholders, such as Distribution System Operators (DSO), Transmission System Operators (TSO), Energy Service Providers (ESP) and aggregators of Renewable Energy Sources (RES) and FlexAssets to: *i)* easily and effectively create advanced Energy Services (ESs), *ii)* interact in a dynamic and efficient way with their environment (i.e. electricity grid) and the remaining of the stakeholders, and *iii)* automate and optimize the planning and the operation of their ESs. In this way, FLEXGRID envisages secure, sustainable, competitive, and affordable ESs. In particular, the main objectives set by FLEXGRID are:

- An Automated Trading Platform (ATP) able to provide as a service the composition and the operation of energy markets
- Automated planning and optimal operation of DSO's/TSO's Energy Services
- Automated Planning and optimal operation of ESP's Business Models (assets and policy)

These objectives will be fulfilled by the development of a service oriented smart grid architecture that offers energy stakeholders several tools equipped with advanced mathematical models and algorithms. These tools will be used for internally optimizing the planning and the operation of the ESs, participating in real time markets of future smart grids, and interacting through markets with other stakeholders in order to meet the highly demanding objectives of future smart grids. Furthermore, it is the idea of FLEXGRID that its software (S/W) platform will be able to host a variety of actors, including: *i)* DSOs/TSOs that want to effectively plan and operate their electricity grid towards low-cost and high-quality ESs (distribution and transmission services), *ii)* progressive ESPs (utilities) that want to provide more advanced ESs and achieve an attractive trade-off between their risks, their profits and the quality of services they deliver, and *iii)* aggregators of RES and FlexAssets that need to address the high volatility and uncertainty of renewables, and offer more competitive ESs (i.e. enhancing the RES "dispatchability" and thus be able to participate in equal terms in the EU energy markets).

In order to validate the methods and tools developed in FLEXGRID, three validation strands are followed in WP7. The first strand focuses on validating aggregator services and will be carried out as pilot tests at UCY's campus grid at TRL 5. This strand will study how the FLEXGRID methods can be used for optimal aggregation of flexibility for different use cases. Furthermore, this strand is also used to validate aspects of the High Level Use Case (HLUC) "HLUC_04 – FLEXGRID ATP offers automated flexibility aggregation management services to ESPs and aggregators" [FleD21].

The second strand focuses on FLEXGRID's services directed towards DSOs and how these can be optimally provided by ESPs. This strand will also be carried out as a pilot using bnNETZE's test system in and around the city of Freiburg, Germany at TRL 5. Here, the goal is to study how the advanced forecasting methods and the collaboration possibilities between the DSO and ESPs developed in FLEXGRID can be used by the DSO for peak-shaving. This strand also validates aspects that are covered in “HLUC_02 – FLEXGRID ATP offers advanced flexibility supply management services to ESPs” [FleD21].

The third strand focuses on validating the Distribution Level Flexibility Market (DLFM) architectures proposed by the FLEXGRID project. This covers an evaluation of the advanced market clearing processes developed in WP5 and to study different TSO-DSO collaboration possibilities within the scope of the DLFM architectures. Strand number three will be carried out as simulations and tests in AIT’s SmartEST lab at TRL 4. By validating the DLFM architectures in the lab, no regard has to be made for current market regulations and other factors that limit what can be implemented in a pilot field trial. Furthermore, lab tests also offer more flexibility in terms of scalability. Both for how many tests can be carried out and for testing the scalability of the FLEXGRID solutions.

This WP is related to the work in WP6 where the FLEXGRID ATP is developed as a software platform or else as a concatenation of three main S/W toolkits. The validations in WP7 will therefore be done in two steps: first using mainly the algorithms developed in WP3, WP4, and WP5, and once first versions of the FLEXGRID ATP are available these will be integrated into the lab and the pilots for further tests.

The main purpose of this deliverable is to present the current state of the demonstration setup plan, the experimentation plan and validation methodology that is chosen for the three validation strands. For each strand, it covers the selected validation scenarios, an initial plan for how the scenarios will be validated, and a general description of the available test infrastructure.

1.2 Scope of the document

The FLEXGRID validations are done in WP7, which has three main tasks focusing on the pilot demonstration plan (Task 7.1), development of the testing platforms (Task 7.2), and execution of the pilot and the lab tests (Task 7.3). This deliverable covers the results from Task 7.1. In further steps in the project, the results from this deliverable will be used for the development and extension of the testing infrastructure. Based on the validation scenarios defined in this deliverable, a development plan will be agreed among involved partners. Once the testing infrastructure has been extended with FLEXGRID algorithms and tools, the validation scenarios will be used as a basis for further development of more specific test cases and detailed experiments, which will be carried out in Task 7.3.

1.3 Structure of the document

This deliverable is structured as follows. Chapter 2 describes the validation methodology that is used for all the validation strands. After this, the Chapter 3, Chapter 4, and Chapter 5 go into the details about each of the validation strands. In order to allow the reader to compare the three test setups, these chapters are all structured in the same way. They start with an overview and motivation of the tests. After this, selected validation scenarios are listed and described. This is also followed by a description of the testing environment and a setup plan. Finally, the deliverable is concluded in Chapter 6.

2 Validation Methodology

The validations in WP7 of FLEXGRID will cover both lab tests at TRL 4 and pilot field trials, carried out at TRL 5. However, both the lab validations and the pilot validations are motivated by the many Use Case Scenarios (UCS) defined in FLEXGRID [FleD21, FleD22]. Also, for both validation cases, the same validation methodology is used. It is based on the ERIGrid Holistic Validation Methodology [Bla16], which is described in more detail below.

2.1 The ERIGrid holistic validation methodology

In the H2020 ERIGrid project [ERI21], a formalized method for testing power system applications has been developed which is being used here in FLEXGRID in order to plan, specify, configure and execute several proof-of-concept laboratory validations. An overview of the overall ERIGrid approach is depicted in Figure 1.

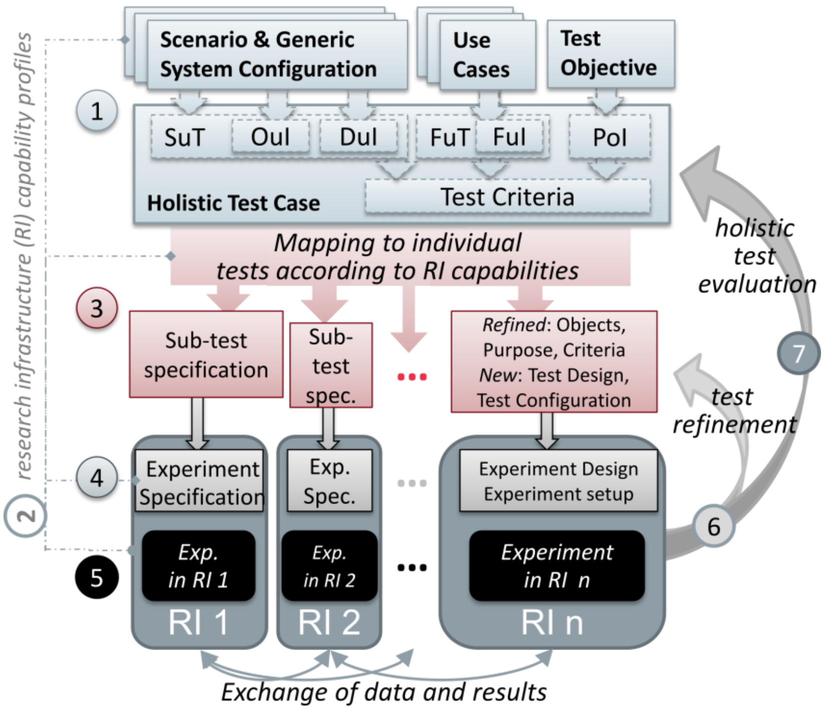

Figure 1: Overview of the ERIGrid validation approach for power systems [Bla16]

The starting point of the ERIGrid validation methodology is the specification of a *holistic test case* (i.e., Step 1). This is derived from a scenario and corresponding system configuration as well as use cases within this setup. Thus, the test case aims to identify specific test criteria, relating to a test system configuration, relevant use cases and a specific test objective. In an independent step, the available Research Infrastructure (RI) – in case of FLEXGRID the lab environment and the pilot environments – is profiled with regard to their testing capabilities (i.e., Step 2).

Depending on the complexity of the validation problem, a test case might be split-up into so-called sub-tests. The sub-tests concentrate on certain components or sub-systems in total reflecting the structure of the holistic test in such a way that the sub-test results may be assembled to offer quantitative feedback on the holistic test criteria. This decomposition is performed in the first part of the mapping step (i.e., Step 3), where the interfaces and dependencies between the sub-test cases as well as the resulting requirements must be specified as well. In a second part of the mapping step, the descriptions of the sub-test cases, given the RI profiles from Step 2, are employed to identify for each sub-test case the appropriate RIs capable of conducting the test. For FLEXGRID, Step 3 can in part be skipped since for the most part the available RIs in FLEXGRID will not be used together for the validations. An exception could be test cases where pilot infrastructure is used together with simulated resources (see Section 3.2.3 for an example of such test case where virtual FlexAssets are used).

Once the RI and tests are known, the experiments can be specified, i.e., the concrete setup and design (i.e., Step 4). In context of carrying out the sub-tests (i.e., Step 5), it is necessary to analyse and to exchange data and results (i.e., Step 6) between the sub-tests, based on which cross-dependencies have been identified in Step 3. For FLEXGRID this would mean a more detailed specification of how the tests will be carried out in each strand.

The results of all tests are analysed and combined to obtain the criteria with which the holistic test is evaluated (i.e., Step 7). Possible methods for combining results might be up-scaling or aggregating results. Thus, the mapping between the tests has two purposes: *(i)* the re-use of results as an input to generate successive results, and *(ii)* the combination of results from different sub-tests to obtain results of the holistic test. To this end, dependencies between tests should be considered beforehand. In FLEXGRID this corresponds to a comparison of the results with what was expected when the HLUC and the UCS were defined.

The mapping step as well as the step of combining results of the sub-test might be an iterative approach. Before setting up and conducting the experiments, the process from holistic test to RI and back should be specified as precisely as possible to minimize the effort and costs.

2.2 ERIGrid validation approach applied to FLEXGRID

Based on the ERIGrid method, a slightly adapted validation methodology was defined for the work in FLEXGRID. It is seen in Figure 2 and is described by the following steps:

1. **Scenario Description:** In the first phase, different Validation Scenarios (VS) descriptions are collected that may be used to validate different aspects that are of interest for the three validation strands. To find these validation scenarios, the FLEXGRID UCS were analysed.
2. **RI Capabilities Profiling:** The second step is carried out in parallel with Step 1. Here, the infrastructure provided in each of the strands is analysed and a profile is made of what can be tested using this architecture. For the two pilots this will be a profiling of the pilot test site and for the lab tests a profile of the lab capabilities will be included.
3. **Mapping:** The mapping step is used to map the identified VS from Step 1 with the RI profiles from Step 2. The most important result from this step is a feasibility check that the scenarios can actually be implemented in the relevant RI.
4. **Experiment Specification:** Following the mapping detailed experiments will be specified based on each VS. Each VS may result in many experiments. The main goal with this step is to make sure that all aspects of a VS is covered. For example, when

the DLFM architectures are validated, an experiment should specify one set of input parameters and Key Performance Indicators (KPI) that should be tested.

5. **Experiments:** Here, the experiments are carried out using the specified equipment.
6. **Analysis:** For each experiment that is carried out, results are collected and analysed. As indicated in Figure 2, an iterative process between steps 3, 4, 5, and 6 is possible and in most cases likely. Consequently, it is also perfectly fine to specify one experiment, carry it out, and analyse it before the next experiment is specified.
7. **Results:** The final step is to combine the results from each carried out experiment. The outcome of this step is the final result of the VS from Step 1.

This deliverable covers Step 1, 2, and 3 in this methodology. For each validation strand, several VS are defined. This is combined with a description and general information about the testing capabilities in the lab and of each pilot site that also shows the feasibility of the selected scenarios for each strand.

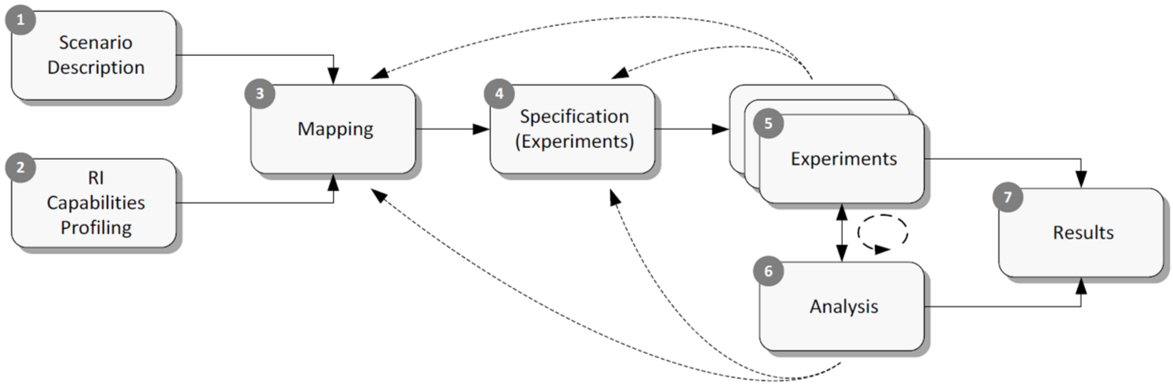

Figure 2: Validation methodology for the pilots and the lab tests in FLEXGRID

3 Automated Energy Flexibility Aggregation – UCY Pilot Setup Plan

3.1 Overview

UCY has set a target of becoming an energy optimal microgrid in the scope of improving the energy efficiency of the campus and its zero energy green objectives. The envisaged establishment of UCY microgrid is expected to make the University energy neutral, rendering it a green university campus. The university campus is currently undergoing new construction infrastructure, while an investment project for the installation of PV systems and battery equipment will be implemented in two phases. The main objective of the microgrid is the transformation of the university campus into a living lab, where the energy consumption will be fulfilled by PV generated energy that is efficiently managed through the effective use of the Battery Energy Storage Systems (BESS). The target is to minimize the energy consumption costs and nullify the CO2 footprint of the university campus.

Flexibility is expected to play a vital role in the future power system. Flexibility can be used to provide technical needs concerning system operation (TSO/DSO), provide better balancing opportunities for trading, for the Balancing Responsible Party (BRP), and provide the requirements for non-dispatchable generation, such as RES, to participate in energy markets. Provision of flexibility has a social, technical and environmental impact, which is aligned with the target set for a clean energy transition. The emerging role of the independent aggregator is key to unlock potential flexibility from distributed energy resources of multiple end users.

The UCY campus comprises of buildings with a heterogeneous set of services and different needs, functional requirements and user experiences. Potential flexibility of these buildings differs according to the type of use and comfort level. Thus, each building (or else end energy prosumer or simply end user) has a different value deviating from its preferred consumption levels. This leads to different flexibility and user parameters, which are key component of flexibility contracts. UCY can unlock and exploit its flexibility leveraging capabilities using load management of certain university buildings resulting in advantages in the future such as:

- Lower carbon footprint
- Lower consumption
- Lower energy bills

The particular infrastructure can be exploited for achieving the aforementioned or form the baseline of an Energy Community that can serve the needs of the University and/or offer ancillary services e.g. when the DSO invokes flexibility for effective congestion management.

The UCY pilot within the FLEXGRID project aims to highlight the role of the independent aggregator in future flexibility markets. Flexibility from DERs can efficiently be traded with profits for the aggregator and participating end-users and a positive impact on the system and the environment.

The DERs of the UCY campus will represent and be used as FlexAssets that belong to the aggregator's portfolio. The scenarios selected to be implemented in the UCY pilot will exploit the UCY infrastructure and demonstrate the potential of FLEXGRID's algorithms to effectively orchestrate and manage the available flexibility and optimally represent it in the market.

3.2 Validation scenarios

The validation scenarios selected to be implemented in the UCY pilot are two Use Case Scenarios (UCSs) of the FLEXGRID project, which involve aggregation of flexibility from DERs. The flexibility of DERs (or else FlexAssets) is represented in electricity markets and managed by the independent aggregator. All information regarding user preferences and constraints and costs of FlexAssets within the portfolio of the aggregator are described in FlexContracts.

The aggregator interacts with the energy market by accepting FlexRequests from the market and by creating FlexOffers towards the market as seen in Figure 3. A FlexRequest from the market requests an amount of energy from activation of FlexAssets for a specific price, while a FlexOffer contains pairs of prices and quantities of flexible energy that the aggregator offers to potential flexibility buyers in the market that better suit its portfolio.

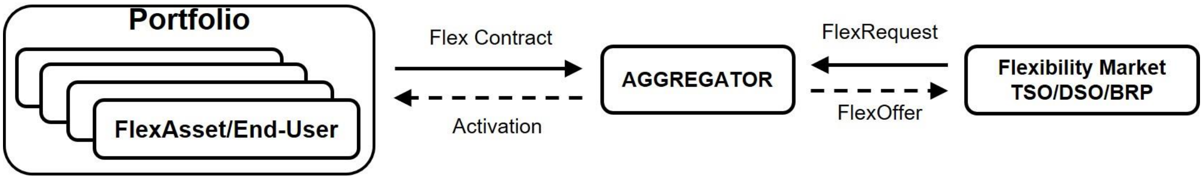

Figure 3: FlexRequest and FlexOffer.

The two UCSs, which will be demonstrated in the UCY pilot focus on managing a FlexRequest from the market and creating a FlexOffer towards the market respectively. The two UCSs with respect to the UCY pilot are described in sections 3.2.1 and 3.2.2. In section 3.2.3, the possibility of extending the portfolio of FlexAssets of the UCY pilot with additional virtual FlexAssets is presented.

3.2.1 VS 1.1: Aggregator manages a FlexRequest

This validation scenario is based on "UCS4.1 – An Aggregator efficiently responds to FlexRequests made by TSO/DSO/BRPs by optimally orchestrating its aggregated flexibility portfolio of end energy prosumers" [FleD22]. The independent aggregator needs to efficiently respond to a FlexRequest made by a FlexBuyer by optimally selecting (in a centralized manner) the dispatch per flexibility asset / end user. A FlexRequest contains a given price for a required amount of energy for specific Market Time Units (MTUs).

When an aggregator positively responds to a FlexRequest, the objective is to maximize its profits from providing the requested flexibility. This translates to maximization of the revenues and minimization of the associated costs. For a given FlexRequest, the revenue of the aggregator is associated in the price of the FlexRequest. The associated costs can be divided into two categories. The first are end-user compensations for provision of flexibility, defined in FlexContracts. The second involves potential imbalance costs, meaning the financial effect of activating flexibility and deviating from the baseline (scheduled energy profile of the flexibility assets). The presence of imbalance costs depends on the interaction of the flexibility market with other stages of the electricity market. As the electricity market in Cyprus is not fully developed (currently no day-ahead or balancing markets), in the implementation of this scenario in the UCY pilot, the focus will be on the costs incurred for acquiring flexibility from end-users.

To efficiently activate flexibility assets within the aggregator's portfolio, it is necessary to determine the scheduled consumption (baseline consumption) of the FlexAssets, to evaluate the flexibility potential of each asset and its associated cost, to communicate with/control the DERs for flexibility activation and monitor the electricity consumption of all assets within the portfolio.

The aggregator can respond to a FlexRequest from a flexibility buyer/flexibility market with a positive or negative response. In case of a positive response, the aggregator is called to manage a FlexRequest. As the FlexRequest contains a specific price for a given amount of energy, the aggregator needs to reach the desired amount of energy through its portfolio, while respecting the cost and utility functions of its end-users. The profit of the aggregator is the revenue (price) of the FlexRequest and the costs are the payments to end-users determined by the FlexContracts. Flexibility activation is established by monitoring the electricity consumption of FlexAssets and comparing with the baseline consumption.

3.2.2 VS 1.2: Aggregator creates a FlexOffer

This validation scenario is based on "UCS4.3 – ESP/aggregator maximizes its profits by dynamically orchestrating distributed FlexAssets from its end users in order to optimally participate in several energy markets" [FleD22]. The aggregator needs to determine/create a FlexOffer, for a given timeframe (i.e. specific MTUs), that best represents its portfolio to participate in future flexibility markets. The FlexOffer should contain prices for given levels of balancing energy, which if cleared maximizes the aggregator's profit and respects end-user preferences and constraints. The aggregator needs to ensure that the balancing energy of any FlexOffer can be provided by the assets within its portfolio and that the requested price of the FlexOffer covers the expenses of activating end-user's flexibility.

The objective of this scenario is to efficiently create FlexOffers based on the assets of the aggregator's portfolio and the corresponding FlexContracts. Once more, the aggregator needs to have information concerning the baseline consumption and establish FlexContracts, which determine the flexibility potential of each FlexAsset for each MTU and its associated cost. This information allows the aggregator to create pairs of prices and energy quantity to offer to the market for each MTU. In this way, the aggregator knows when submitting a FlexOffer, for a pair of price and energy quantity which FlexAssets will be activated in case it is accepted by the market.

In case a FlexOffer is accepted, the aggregator needs to activate the FlexAssets, which participated in the accepted pair of quantity and price for the specific MTU. Control/communication of FlexAssets is necessary to acquire/activate the flexibility and real-time monitoring of electricity consumption ensures the deviation from the baseline consumption.

3.2.3 VS 1.3: Extension with Virtual FlexAssets

The portfolio of the aggregator in the two validation scenarios presented in the two previous sections consists of FlexAssets/DERs of the UCY pilot. In order to further enrich the portfolio and allow demonstration of more diverse portfolios, virtual assets can be added to the portfolio. The algorithms will run on this new extended set of FlexAssets. In all outputs where flexibility is selected in DERs of the UCY pilot, activation and deviation from scheduled consumption will be monitored in the pilot. The response of virtual assets will be estimated and simulated. The respective results will help the UCY pilot to plan its future RES/FlexAsset investments in a way that fulfils its goals in the long term. This validation scenario will be implemented in collaboration with WP6 partners and via the use of FLEXGRID ATP and the frontend services of the AFAT.

3.2.4 Initial validation plan

The two UCSs that will be validated in the UCY pilot have similar objectives and share the same functionalities and test criteria.

In order to investigate the flexibility management process by the aggregator, the baseline consumption of the participating assets needs to be established along with the cost associated with flexibility activation for each asset (FlexContract). In a second stage and within the first UCS context (i.e. “Manage a FlexRequest”), it is needed to construct realistic external FlexRequests, which can be satisfied by the available controlled flexibility within the UCY pilot. In continuation, the developed algorithms of the responsible partners for these two UCS, UCY and ICCS respectively, will be used to manage the available flexibility of the UCY pilot.

The majority of the available flexibility stems from the cooling system of the UCY campus. The consumption of the cooling system depends on external weather conditions. The electricity consumption for a day in July and in January is shown in Figure 4 and Figure 5 respectively.

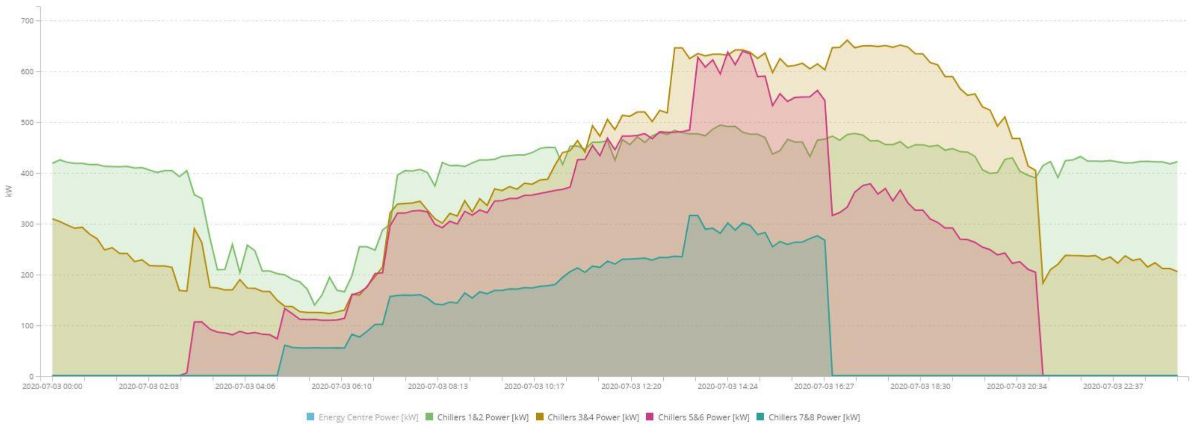

Figure 4: Electricity consumption of UCY cooling system on 3/7/2020

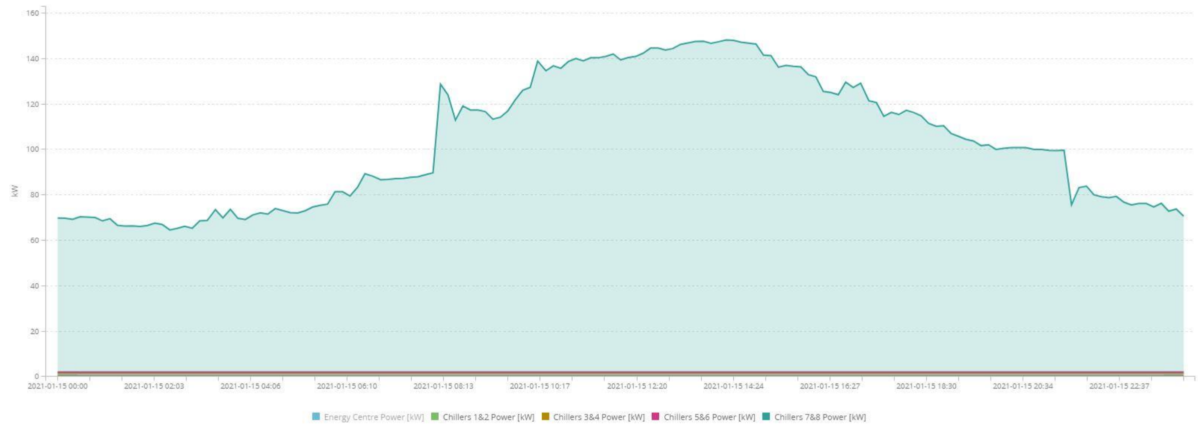

Figure 5: Electricity consumption of UCY cooling system on 15/1/2021

It is shown that the electricity consumption increases significantly in warm periods. This translates to larger amounts of flexibility in the period of May-October. In order to have more flexibility available from the UCY pilot, the demonstration of the validation scenarios should be performed in the summer period.

3.3 Pilot environment and setup plan

The University of Cyprus (UCY) campus infrastructure will be utilized in the FLEXGRID project to investigate the potential of FLEXGRID to efficiently manage through aggregation the flexibility of multiple tertiary buildings within a microgrid infrastructure.

3.3.1 Pilot setup

The whole university is currently operating as a microgrid with a hierarchical architecture:

- At the top tier, a controller is responsible for balancing the energy demand and production by coordinating the second-tier controllers.
- The controllers on the second tier are the Building Energy Management Systems (BEMS) controllers of each building. Their responsibility is to coordinate the electromechanical systems of each building, in order to achieve the goals, set by the top tier controller.

The second-tier controllers use an array of sensors throughout each building that get information about the state of the building. In parallel to the second-tier controllers, there are data acquisition devices at each distribution transformer, serving the campus and record and transmit data regarding energy consumption and quality to the main controller.

The electrical connection of the university campus with the distribution grid appears in Figure 6. The voltage at the Point of Common Coupling (PCC) of the university campus with the distribution grid is at MV and more specifically at 11kV. As it is shown in Figure 6, within the university campus exist several distribution transformers, which reduces the voltage level to 400V (three-phase voltage system). University of Cyprus has access to the data at the PCC, regarding the magnitude of the current at each feeder (two feeders totally).

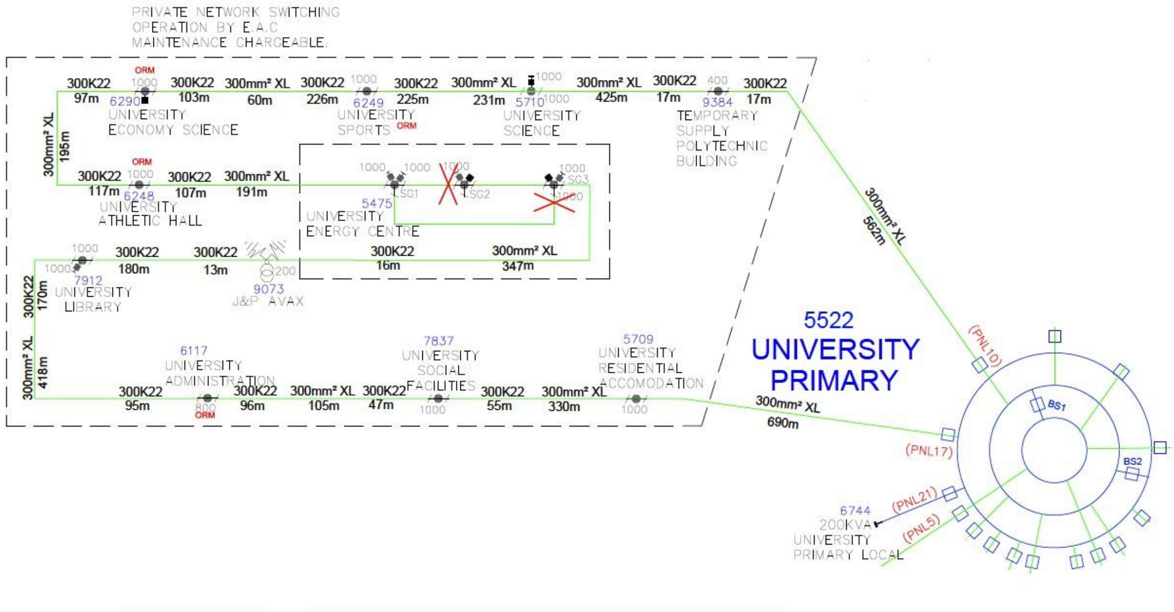

Figure 6: University line diagram.

The main electrical load of the university is the cooling system, which is placed centrally at the Energy Centre (ENC) building. The heating takes place by operating an oil heater, while the cooling is carried out by electrical chillers. However, taking into consideration the climatic conditions of Cyprus, both the heating and cooling are operating for a certain period of the year. Since during the summer period, the temperatures in Cyprus are quite high, the cooling needs are significant. For this reason, the electrical chillers are identified as a flexible load that can be smartly traded through their effective control.

The cooling system operates by circulating low temperature water through the buildings of the university using a district cooling network shown in Figure 7. In Figure 8, the schematic of the Energy Centre connections to UCY buildings and the BEMS connections are shown.

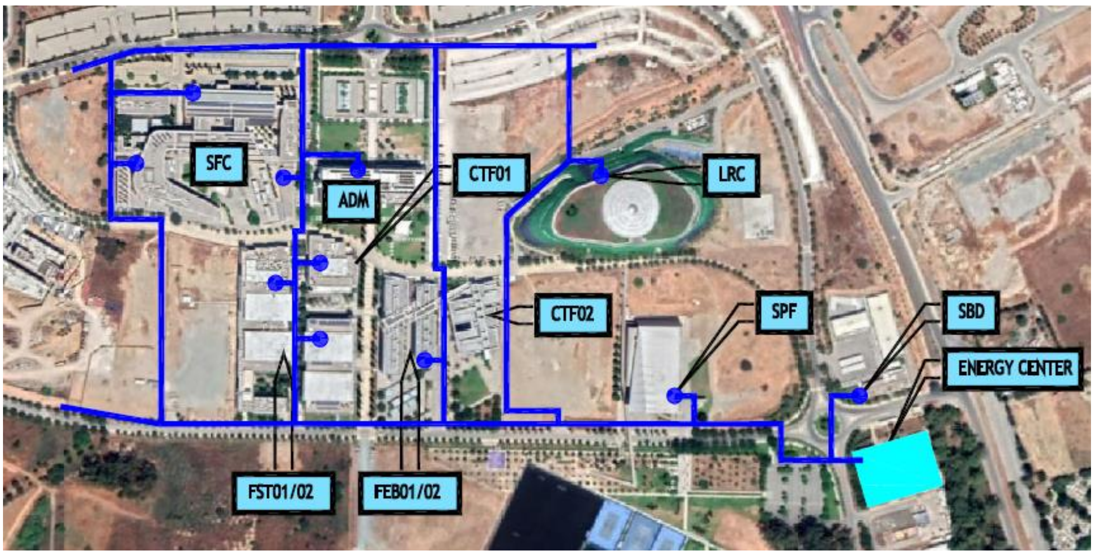

Figure 7: UCY campus district cooling schematic.

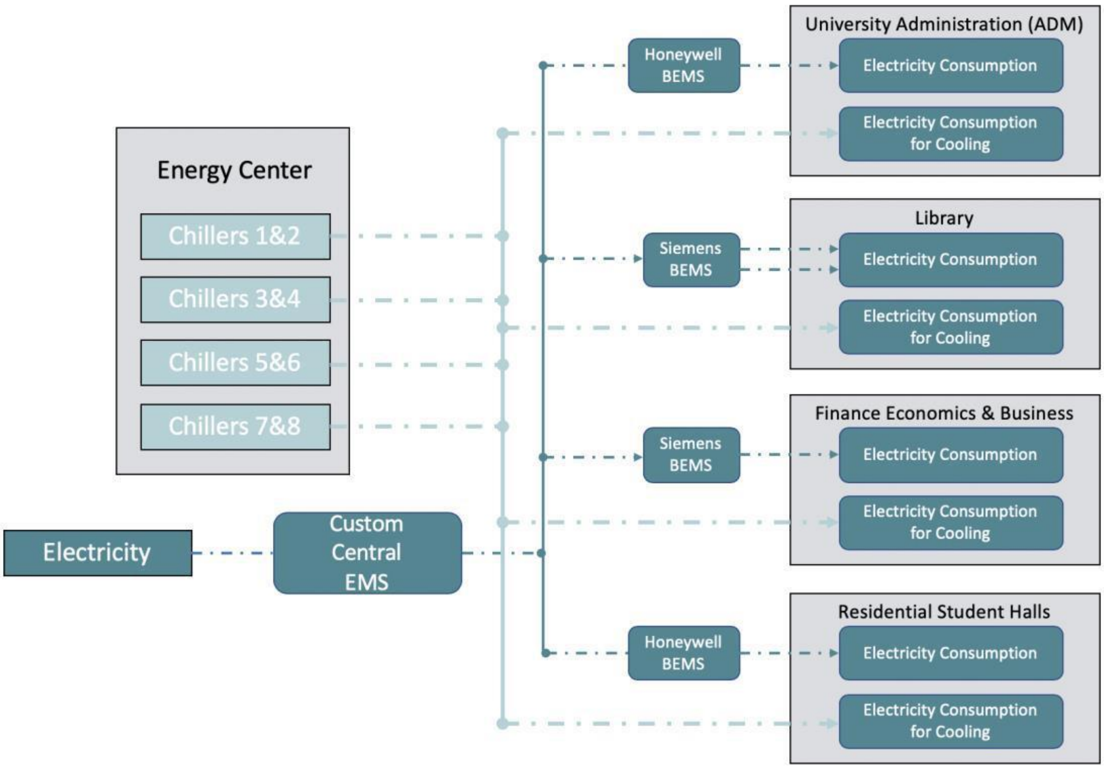

Figure 8: Schematic of ENC connections to UCY buildings and the BEMS connections.

Flexibility leveraging can be realised by appropriately modifying the temperature control of each floor of participating buildings through the corresponding BEMS as seen in Figure 8.

The BEMSs of the campus buildings, which will participate in the UCY pilot for the FLEXGRID project are/will be connected to a Complex BEMS (upper layer control platform), which allows control of the cooling operation of each floor of the building through a selection of operation modes as follows:

- Normal mode: Local Building Management System (BMS) control the floor, not Complex BEMS.
- Automatic mode: Complex BEMS controls the floor with operating parameters from local BMS.
- Power Save mode: Complex BEMS controls the floor with increased operating temperature interval in rooms. This mode allows the temperature of the building to increase which reduces energy consumption and in turn the load of the chillers.
- Power Boost mode: Complex BEMS controls the floor with decreased operating temperature interval in rooms. This mode reduces the temperature of the building which increases energy consumption and in turn the load of the chillers.

It is possible to change separately the operating mode of the cooling system of each floor within a building, thus providing several options for altering the consumption of the building (multiple setpoints). For improved flexibility control of heating and cooling of the buildings as well as shorter time of response, energy valves will be installed at the inlet/outlets of the buildings' water pipes instead of the previously used fan coils. Through the central platform (Complex BEMS) it is possible to monitor the status of the connected BEMS and the electricity consumption of the electrical chillers (Figure 9 and Figure 10).

Figure 9: Control of operating mode of cooling system in a building of a connected BEMS.

Figure 10: Monitoring of energy consumption in UCY pilot.

3.3.2 Setup plan

The flexibility of the participating building of the UCY campus will comprise the aggregator's portfolio. Along with FlexContracts that describe user preferences, constraints and cost, the aggregator user will be able to have all information necessary for its portfolio. The flexibility of the participating buildings will be managed through the developed algorithms, which will run in the FLEXGRID ATP (i.e. AFAT backend) and the outputs will determine which assets of the UCY campus need to be activated.

The activation of the flexibility will either be implemented by an Application Programming Interface (API) of the central platform or by creating/communicating a signal requiring action from an administrator of the central platform. The activation of flexibility, deviation from baseline can be monitored through the central platform for the affected timeslots. Profits of the aggregator will be calculated based on the FlexContracts of participating buildings and their contribution to activated flexibility. Access to that information will be implemented either via an API or by external communication through an administrator in order to visualize the respective information in the FLEXGRID ATP (i.e. AFAT frontend).

4 Evaluating Forecasting Methods for DSO Services – bnNETZE Pilot Setup Plan

4.1 Overview

There are three major trends in Germany right now, which have a strong influence on distribution grid operation in the future but also on energy markets right now. Therefore, they shall be taken into account regarding the tests planned to be conducted in the bnNETZE's pilot test site:

1. **Transition to an electricity system completely based on renewables:**
   In the revised national 'Renewable Energy Act' the determined goal is that all electricity in Germany will be generated in a greenhouse gas-neutral manner before 2050 and that the share of renewable energies in gross electricity consumption will be increased to 65% in 2030. All nuclear power plants are expected to be shut down until the end of 2022; and all coal fired power plants until the end of 2038. Thus the operation of the electrical system is expected to become much more volatile than it is today. This will lead to more interventions by the grid operator to ensure a reliable supply, but will also lead to significant price volatility in the energy markets. So control of available FlexAssets is bound to become more and more relevant from a grid operation's perspective, but also from an economical point of view.
2. **Marketing of PV energy:**
   Furthermore, the first renewable systems fall out of the guaranteed feed in tariff system provided by the national 'Renewable Energy Act' (EEG). The EEG provided fixed feed in tariffs that had been guaranteed for twenty years. This offered the investors a long scale security of investment. At the end of 2020, this period came to an end for the first RES installations in Germany. This was the first dropouts occurred and over the following years thousands will follow. As a result, the affected system owners should now decide whether or not to phase out their installations, to look for a direct marketer, to use as much energy as possible in their own premises, or to accept the low market-oriented price given by the DSO for a transition period until the end of 2027 (only available for PV installations below 100 kW).
3. **Systemic regional imbalance of generation and consumption in Germany:**
   In accordance with 'Energiewende', the German nuclear phase out will discontinue the last of the country's nuclear plants by the end of 2022. As mentioned above, the last coal plant will be shut down at the end of 2038. It is a continuous process, and the first plants will be offline as early as 2021. The continuous shutdown of these large thermal plants will further amplify the energy disparity between the north and south of Germany, because most wind energy production capacity is located in the North around the shores of the Northern and Eastern Sea, as well as offshore. According to experts at the German energy supplier EnBW, the south of Germany has always been an energy importer due to the fact that the installed capacity was never enough to cover the peak loads. This effect will now be intensified.

Figure 11 illustrates the renewable energy feed-in in the North and South of Germany, with the north having an abundance of wind energy and the south having great solar PV implementation. Further pump storage plants in Norway shall be included and help as a type of long-term battery storage. They will be interconnected by new and already existing undersea cables. However, the transport capacity within Germany is not yet available and there have been significant delays in the construction of the new transmission line ‘Suedlink’. Thus, a supply gap is expected for southern Germany already in 2024 (see Figure 12).

Figure 11: Renewable energy disparity between North and South of Germany

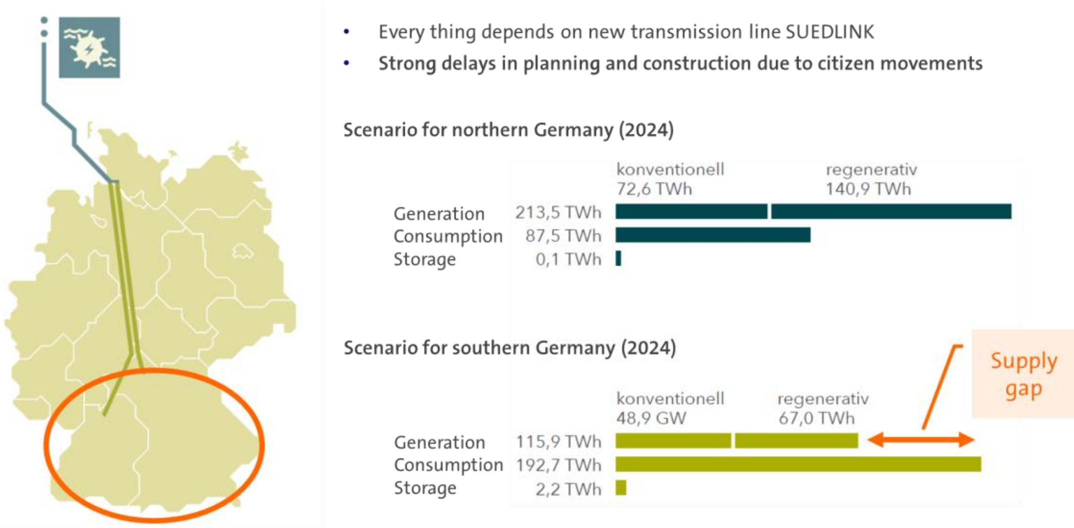

Figure 12: Expected supply gap for Southern Germany in 2024

As the grid becomes more reliant on renewable energy sources, it is important to ensure that the grid also enhances its flexibility capacity. Unlike coal and nuclear plants, wind and solar power is not dispatchable in the sense that the given supply cannot be easily increased or decreased to match power demand. Weather parameters can be volatile and are not easily predictable. Demand side management techniques have helped alleviate the chances of the grid collapsing, however, time has come for a more robust approach.

In Germany, a new system will be established by the end of 2021, forcing all generation units – irrelevant if owned by utilities, companies or private personnel – to take part in an obligatory system for remote control. In case of congestions on higher grid levels, requests are generated and sent from the responsible grid operator to the grid operators of the lower levels. They have to select and control distributed devices in a way, that congestion on the higher level can be avoided. The DSO is also responsible for avoiding congestions in its own distribution grid. This new national concept called 'Redispatch 2.0' is enforced by law and it must be implemented by the end of 2021.

The bnNETZE team has already identified these major trends and works on 'translating' them in several research problems and pilot validation scenarios as explained in the following.

4.2 Validation scenarios

All main objectives listed above lead to a much more advanced control of flexible generation and consumption devices on distribution grid level from the perspective of a reliable grid operation (cf. DSO), or from the perspective of generating additional revenues by flexibility marketing on more and more volatile spot / intraday markets (cf. profit-based ESP company). For both purposes, accurate forecasts are essential.

The validation scenarios for the bnNETZE test site take this into consideration. Therefore, the schedule for the pilot test site is divided into three periods:

Period 1 is based on simulations and theoretical analyses. It will initially focus on three forms of forecasting:

1) PV Forecasting,
2) Price Forecasting,
3) Load Forecasting.

In order to assist the partners in training their algorithms, bnNETZE will provide:

I. Historical data regarding real prosumers (generation / consumption)
II. Historical data regarding a representative mix of PV installations
III. Historical data regarding physical energy flow through the entire bnNETZE grid
IV. Historical energy prices on European Power Exchange (EPEX) (day ahead and intraday)
V. Historical prices for auxiliary energy in balance group settlement

Once the associated partners have trained their algorithms for forecasting, bnNETZE will analyze the forecasted values and compare them to the real measurement values. In an iterative process, bnNETZE will improve forecast accuracy together with the research partners (i.e. UCY and AIT) and analyze the relevant drivers for significant deviations.

Furthermore, bnNETZE will take out an economical simulation for dedicated PV-installations dropping out of the national feed in tariff system. For real installations, bnNETZE will simulate the possible revenues by marketing the produced energy on EPEX in the spot and intraday market taking into account the necessary costs for updating the technical installations and metering devices. Starting with these singular systems, bnNETZE plans to generalize the outcome to stipulate general statements regarding the potential of added value due to flexibility marketing.

Period 2 is focused on setting the technical stage for the real pilot test site operation. Many validation tests are necessary to prove that all relevant datasets from bnNETZE pilot test site are available, are transmitted and are translated correctly to be read by FLEXGRID ATP - and (on the opposite direction) FLEXGRID commands can be understood and executed by the pilot test site.

Period 3 is dedicated to the real pilot test site operation. As mentioned above, bnNETZE will compare the forecast results from FLEXGRID ATP to real measurement data and the forecasts coming from a grid control system aligned to the national Redispatch 2.0 approach. Furthermore, we intend to follow a peak shaving approach covering the entire bnNETZE grid first to avoid unnecessary costs for grid usage regarding the upstream voltage level (cf. fees paid to the upstream TSO), and secondly to reduce congestions in the distribution grid.

4.2.1 VS 2.1: PV forecast

PV-Forecast in high accuracy based on at least hourly resolution is essential to handle all market and regulatory trends listed above. In cooperation with the University of Cyprus (UCY), existing forecasting algorithms will be improved. These algorithms will be trained on the basis of real data from PV systems in the grid of bnNETZE together with weather forecast data like e.g. radiation and temperature from an external weather service provider.

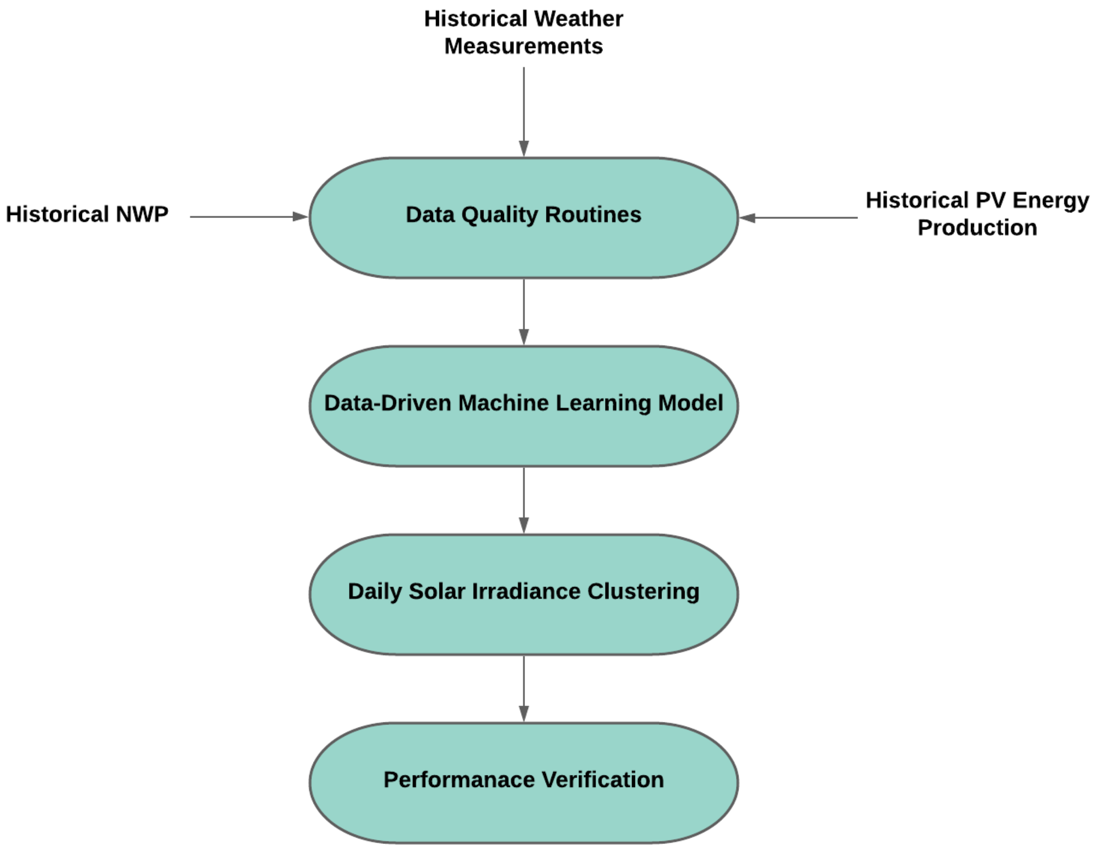

Figure 13: An overview of UCY's PV forecasting methodology

UCY is using a Weather Research and Forecasting model together with a PV Power Day-Ahead Multiple Regression model to provide a robust forecasting approach. This novel technique of combining machine learning and expert systems, with additional data aggregation is a strong initial approach. Figure 13 shows an overview of UCY's PV energy forecasting method.

Considering that real values for PV data occasionally display invalid measurements due to system inadequacies or outages, data integrity is essential for the reliable analysis of PV systems. The UCY team has developed an integrated methodology for PV data processing and quality verification. To ensure data quality, software routines were developed to detect invalid data and replace those values with alternative, but intelligent calculations that would replicate real values through inferencing techniques. For the correction of actual data, UCY is utilizing both the Kalman Filtering and Moving Average techniques. Kalman filtering can be used for any data set that may contain uncertain information. This approach is best for systems that may be continuously changing and has some aspect of unpredictability, as weather does. The Kalman filter produces an educated guess based on all other given data in order to replace that ineffective data points [Kim18]. Using the Kalman Filter method with Moving Average, which is a statistical approach that would calculate a series of averages for a given duration of data, would determine reasonable values for invalid measurements that were caused by unavoidable system failures.

After verification they will use the data provided by bnNETZE to determine the deviation of the predicted values vs the real measurements. The relative root mean square error (nRMSE) will be utilized as an accuracy indicator for the forecast. The nRMSE is the metric often used when the result needs to be normalized to a relative value to facilitate comparisons. After evaluating the first forecasting attempt, bnNETZE and UCY will collaborate on suggestions that could be implemented to address any inefficiencies or outliers.

4.2.2 VS 2.2: Price forecast

For flexibility marketing, spot trading as well as intraday trading are especially interesting. Spot trading takes place one day ahead for 24 hourly timeslots of the following day. Intraday trading is executed in the running day until one hour ahead of the execution time. The resolution here is quarter hour. In addition to PV Forecasting, UCY will also be the associated partner for market price forecasting. bnNETZE will provide historical energy prices from spot market as well as intraday trading originating from EPEX, which is the most relevant energy trading authority for Germany, France, Austria and Switzerland.

A pivotal aspect of energy markets from the perspective of a flexibility provider and energy service provider are forecasting methods. Renewable energy sources are an imperative aspect of Germany's electricity market, so it is important to understand how electricity generation from wind turbines and photovoltaics, along with weather dependent variables like radiation, wind speed and temperature impact future electricity prices.

The chosen forecasting methods are not scientifically novel; however, they are a prerequisite in terms of the much bigger picture of flexibility marketing. Forecasting the electricity market price is important because electricity demand is highly dynamic depending on the time of year, weather, and human activity; therefore, it is more susceptible to volatility. Extreme peaks or dips of energy usage are extremely interesting from a flexibility market perspective. If the algorithms are trained well enough, they could predict and capture the intervals with extreme highs and lows of energy price. Thus, an ESP would be able to purchase and store energy when it is offered at a negative price and sell it later to maximize the profit when the market price increases again.

According to financial experts, using a simple forecasting approach based only on historical values would be extremely difficult to capture the volatility of electricity price, which has a higher volatility than any other financial asset by a magnitude of two [Wer14]. In forecast modelling, it's not necessary that all variables have linear relationships. For this forecasting situation, UCY has opted to use an ELM (Extreme Learning Machine) algorithm. Figure 14 below shows the comparison of different forecasting algorithms and their Mean Absolute Error (MAE). ELM was the first choice as it is a simple and computationally cost-effective method. The UCY team believes that ELM in combination with other methods will improve their methodology for forecasting of both the actual hourly prices and the outliers that are expected for electricity price.

Literature - Research Papers

Other Models	Winter	Spring	Summer	Autumn
	MAE	MAE	MAE	MAE
ELM	2.03	2,30	10,16	7,32
BPNN	2,36	2,23	11,00	7,82
RBFNN	2,10	2,64	10,88	7,96
W-KELM	2.62	0,84	1,02	3,30
ARIMA	5,97	-	-	-
ANN	5,53	-	-	-

Figure 14: Comparison of MAE for different price forecasting methods

4.2.3 VS 2.3: Load forecast

Last but not least, forecast algorithms for physical load flows shall be elaborated. In this validation scenario, bnNETZE works in cooperation with AIT in Austria. bnNETZE will provide physical data regarding the real energy flow in and out the entire bnNETZE grid. The aim is to train AIT's algorithm and to improve its accuracy, so the load of the following day can be forecasted in quarter hour intervals precisly. This is requested from all DSOs covered by the German Redispatch 2.0 regime. Additionally, it is also interesting for a DSO to save real money by activation of dedicated flexibilities to avoid peak loads – and associated high grid usage tariffs that should be paid to the upstream grid operator (i.e. TSO).

The method of 'Recurrent Neural Network' (RNN) was chosen as it has shown the most promising results in previous forecasting projects. One of the most widely used methods of forecasting is Artificial Neural Networks. Similar to Artifical Neural Networks, RNN consists of multiple inputs and contains a hidden layer of neurons that assign a weight to each of the input neurons before providing an output or predictive value. Additionally, RNN take the patterns of the inputs into account as well as patterns they learn as the algorithm is being trained. A quantitative forecasting approach can be used when the following two primary conditions are met: *1)* historical data is available *2)* One can deduce that the patterns of the past would repeat in the future to some extent [Hyn 18]. Since the goal of this pilot is to predict future values using historical data as one of the input parameters, using RNN as the forecasting method is an appropriate approach for this time-series model. For horizon metrics, AIT will use dynamic time warping and 24-hour consumption deviation. AIT also plans on taking a hybrid "data driven & rule-based systems" approach.

4.2.4 VS 2.4: Peak shaving

One superior business case, which will be analyzed within FLEXGRID is preventing peak loads in the entire grid from the perspective of the DSO. DSOs in Germany pay a grid usage fee to the upstream network operator for the maximum power at the transfer points (or else points of common coupling). Typically, load peaks in the grid occur in the morning, around noon or in the evening. When connected to a superior entity, DERs could offer their flexibility potential to the DSO in order to avoid peaks in the grid. Keeping that in mind, the test sites intend to establish a setup where the DSO can use the flexibility potential of DERs as a means of peak shaving.

Figure 15 illustrates the peak shaving approach. It is common in Germany that a DSO has to pay a grid usage fee for the highest physical peak load in the grid. The highest quarter hour value is relevant for settlement and clearing. If it is possible to forecast the expected time precisely, it is possible to activate flexibility in the grid accordingly, and to reduce this expected peak load. This brings great financial value over the span of the year. All peaks coming later can be kept under this new limit, too.

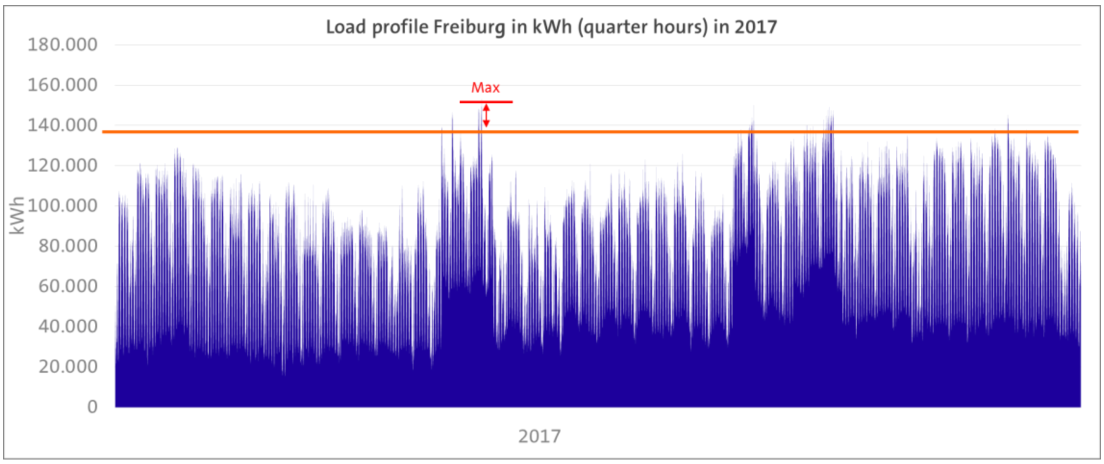

Figure 15: Peak shaving example for the entire bnNETZE grid

4.2.5 Initial validation plan

No form of forecasting will always be 100% precise, but the hope is to be able to foresee major peaks or dips in the energy market. In order to validate the forecasting approaches that the respective partners are taking, there are a couple of different validation strategies that can be used. The simplest comparison for forecasted data versus actual usage would be to use a multiple linear regression model. Although it is considered an uncomplicated method, this would provide an initial snapshot at how accurate the forecasted values were. For this pilot, the regression model must be able to capture the weekly pattern or seasonal variability. Another more complex approach that could be used is an ARIMA model or a SARIMA model [Hyn18]. Autoregression modelling essentially takes previous data into account to predict future values. Several different research articles show that this would be a valid approach in comparison to forecasted values versus real time usage.

bnNETZE has already provided the associated partners with historical data that was significant for each one of their forecasting methods. Once the respective partners simulate an initial run of their algorithms and provide their predicted values, bnNETZE will then validate these values by assessing the forecasting accuracy. Accuracy metrics or errors can be categorized into 3 widely used categories, scaled, scale-dependent, and percentage errors [Hyn18]. The most common indicators for each category are, MAE, Root Mean Squared Error (RMSE), Mean Absolute Percentage Error, Mean Absolute Squared Error. The two most commonly used metrics are MAE and RMSE. MAE determines the average degree of error in the forecasted outputs and does not take into account whether it is a negative or positive error. It is one of the most widely used accuracy indicators for forecasting because it is easy to interpret and compute [Chai14]. Similarly, RMSE also determines the average degree of error in the predicted values and is indifferent to the direction of the error. However, unlike MAE that assigns an identical weight to all errors, RMSE assigns a more significant weight to larger errors. This is due to the fact that the errors in RMSE are squared before the average of the errors is taken [Chai14].

The bnNETZE team is encouraging partners to not rely on MAE as their sole accuracy indicator as it is a very simple method to use for complex forecasting models. The proposed accuracy indicator to use is RMSE. For the pilot site, it is particularly relevant to capture peaks in the data and a large variation is undesirable. RMSE assigns a greater weight to larger errors, so it is better suited for the goals of this pilot in comparison to MAE.

Once the deviation is determined, feedback will be provided on how UCY and AIT can train their algorithms to be improved. Alternatively, it could be suggested that the chosen algorithm or inputs used are not effective for the forecasting goals and another approach must be taken. Although there is not one approach that is deemed to be the “best”, bnNETZE would want the research partners to train their algorithms to be able to capture as many outliers as possible.

As described already above pilot operation will be divided into three periods (see Figure 16):

1. The first period (1st January 2021 until 31st of July 2021) focuses on simulations and theoretical analyses. Control of real devices is not intended. The goal is to set the

stage for any forward-looking flexibility management in relation to reliable grid operation, as well as creation of additional value by marketing flexibilities on the EPEX. The initial step will be to work on the implementation and improvement of several forecast algorithms in conjunction with FLEXGRID research partners. Additionally, we will conduct an economic analysis regarding the market options for PV systems that are no longer covered by the regulated feed in tariffs.

2. Partly in parallel, the second period (1st of April 2021 until 30th of September 2021) will focus on preparing the real test site consisting of one large battery storage and ten private energy prosumers that will provide bnNETZE control access to their facilities. The central motivation is to get all devices, as well as communication links, operational and to program the protocol converters between bnNETZE's test site and the FLEXGRID ATP.
3. The third period (1st of October 2021 until 31st of July 2022) will be dedicated to real operation of the test site controlled by FLEXGRID ATP and its algorithms. The goal is to show that the system works reliably and contributes to the main objectives as mentioned above. This will confirm the precision of the FLEXGRID forecasts. For this purpose, real measurement values and comparative forecasted values from our grid control system (still to be implemented within the frame of the national Redispatch 2.0 concept) will be taken into account. Subsequently, the approach of peak shaving for the entire bnNETZE grid will follow. This helps to avoid congestions in the upstream voltage levels.

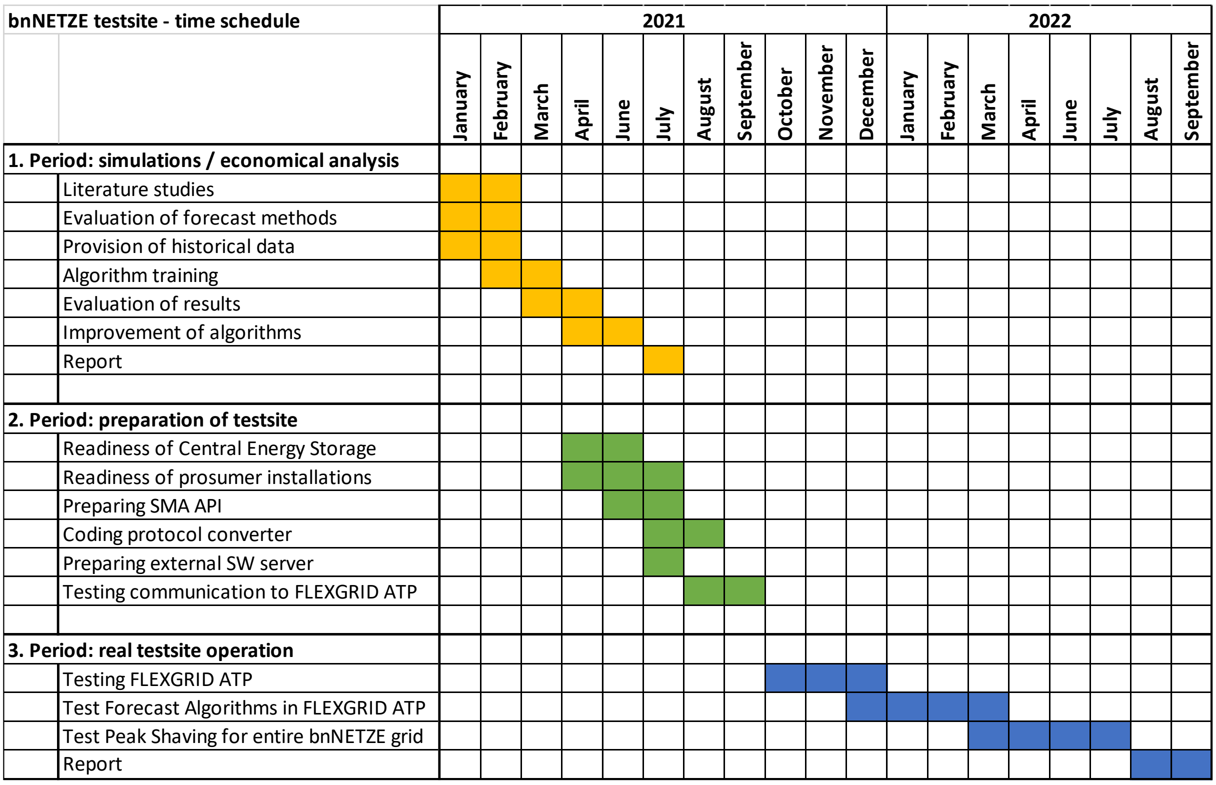

Figure 16: Time plan for bnNETZE pilot test site operation

4.3 Pilot environment and setup plan

Partly in parallel to the analytic work started in the first period, bnNETZE's real test site will be set fully operational until October 2021. Therefore, an already existing large battery storage asset has to be interconnected to the FLEXGRID ATP. In tandem, ten end energy prosumers will voluntarily take part in FLEXGRID project and give us control access to their devices.

4.3.1 Pilot setup

The bnNETZE pilot focuses on a hybrid approach. On one hand, it will provide one Centralised Energy Storage asset (CES). On the other hand, it will provide a total of ten real-life end energy prosumers with Distributed Energy Storages (DES) in private households.

4.3.1.1 Centralised Energy Storage (CES)

The Green City Freiburg in the south-western corner of Germany has about 220,000 inhabitants. Freiburg is one of the sunniest regions in Germany, experiencing a great penetration of renewable energy sources especially photovoltaics. Further development and use of renewable energies is not limited by a lack of resources, but more and more often by the lack of capacity in power lines leading to the outskirts of the city. Due to the relatively high sun radiation in the south-west compared to other regions in Germany, PV systems are widely installed and used in this region and often connected to the low voltage grid. Feed-in peaks during sunny days with low power consumption currently already require new strategies to cope with congestion management and occurring voltage peaks.

The already existing CES asset deals exactly with this problem in a rural grid area. It is located at an end-feeder in the suburb "Freiburg-Opfingen", which is a community remote from the main city of Freiburg and located at the outer rim of the distribution network. Figure 17 shows the location of the CES.

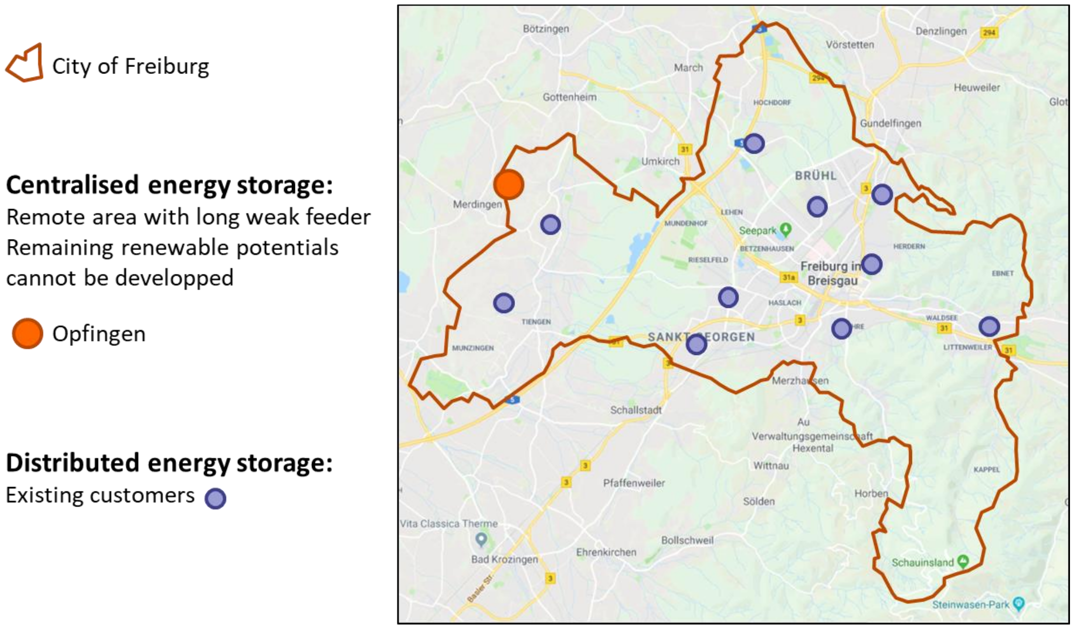

Figure 17: Location of centralized energy storage

Nevertheless, this region is predestined for PV-systems, because it's settled with many farmhouses with barns and extended roofs. This is perfectly suitable for the configuration of PV-modules. In the selected case, a farmer's house is located at the end of a feeder. The property is equipped with four PV plants with a total installed power of 30.5 kW_p. All four PV plants are connected via one single grid connection point to the public low voltage grid.

The distance between the next substation and the end of the feeder is nearly 840 m. On the substation, other feeders with PV generation are connected. Overall, an installed PV power of 331,8 kWp is connected to this point. During sunny days, this already results in a voltage increase in this specific geographical area. This effect is intensified towards the end of the long feeder due to the energy feed in of the PV-systems on the farmer's house. In fact, voltage limits at its grid connection point are violated by the local generation of electricity several times over the year. A further extension of the existing PV systems is not possible, even if there is more than enough free space left on the barn's roof.

The voltage on the grid connection point of the farmer's house can rise up nearly 7.5% above the regular level on a day with maximum generation from the PV-Systems and regular load. 3% voltage deviation is allowed at maximum by German regulation. Due to the geographical distance of the PV installations on the roofs to the grid connection point of the farmer's house, the voltage increases further along the electrical line running on the property. Thus, there are situations, where the acceptable voltage tolerance level of 10% at the connection point of the inverters is exceeded. In such cases, the inverters shut down automatically and the PV-systems are no longer able to generate electricity. In consequence, the PV-system owner loses the guaranteed feed-in tariff for the not produced energy and demands compensation for lost revenues from the grid operator. Hence, a strong interest on both sides exists, that this event is avoided in any case.

By using a battery storage system, the PV plant is able to fully feed-in into the local distribution grid even during peak production periods. Generation peaks of the PV plants are fed into the battery system. As an example, by cutting the generation peaks during the main production times between 12 a.m. and 5 p.m. on sunny days, the distribution network can be significantly relieved. During night-time, the stored energy is transported without causing any problems over the low stressed line. The battery management system decides locally, if the battery should charge or discharge or just stay idle for the first goal of the CES, which is to ensure entire feeding-in of the PV plants and maintaining the voltage within acceptable level. As a result, the battery works as a grid-friendly component in regular operation mode.

Due to the volatile PV production, the battery may not be required during all days and seasons of the year. Moreover, the battery might have some flexibility potential even when it is needed to ensure feeding-in of the PV plants. It is possible to override the local control for limited time periods with external control commands issued by the FLEXGRID ATP. These are the windows for FLEXGRID ATP to use the flexibility of the CES for other purposes.

Figure 18: Redox flow battery container

This case is an excellent example of how a battery storage device can help to secure full generation of renewable energies without expensive grid enforcement. At the same time, new potentials for expanding existing PV-plants on the roofs with more panels connected to the unchanged weak feeder, can be tapped. Last but not least, the flexibility of the battery can be used for flexibility marketing. The pilot also establishes that a battery can serve separate use cases and value streams.

A vanadium redox-flow battery is used as the centralised energy storage, as seen in Figure 18. The capacity of the system is 120 kWh and the usable capacity is 108 kWh. The power is limited by the stacks and the bidirectional power inverter to 20 kW.

The advantage of redox-flow batteries is that power and capacity can be scaled independently. The capacity depends on the size of the electrolyte tanks, which are vanadium-based. Thus, the power depends on the stack. Furthermore, the redox-flow battery has the ability to cycle with a depth of discharge of more than 90 % with no lifetime capacity loss, a high cycle life of up to 20,000 cycles, is fully recyclable and inherently safe. The storage system is installed outdoors, accommodated within a container. Three communication links via LTE-Modems are available:

- Grid control centre of BADENOVA
- Storion USA for testing purposes
- FLEXGRID ATP

4.3.1.2 Distributed Energy Storages (DES)

The connection of prosumers, equipped with PV-systems, distributed energy storages, home management systems and partly EV charging facilities is the second part of the hybrid pilot implementation of bnNETZE.

Nowadays, the costs for self-produced energy from a home solar system is about 20 ct/kWh, which is lower than the energy bought from an energy supplier. This is one reason why the number of new installed PV systems is high in Germany. Because of the significant lower price, there is a strong incentive to use as much as possible of the self-produced energy. As a result, the market for private PV storages developed rapidly over the last few years. Today, more or less, all new PV systems are sold together with a PV storage as well as a home management system to maximize self-sufficiency and to minimize expensive energy supply from a utility company (or else energy supplier/retailer).

The pilot test site focuses on testing additional flexibility potential of households that is already optimizing their self-sufficiency with a home management system, evaluating the business idea in means of supporting a reliable grid operation and financial market potential as well as testing the technical feasibility of the setup.

The home management system takes the role of a local energy management authority at the unit level. But the management over other households' energy needs and the needs of the electrical grid are missing. Since SMA company is the market leader for solar hardware in Germany, BADENOVA (and thus bnNETZE) seeks for strategic cooperation opportunities with this company. On the other hand, SMA already provides a widely used home management system called "Sunny Home Manager" (see Figure 20), which is capable of making forecasts of PV-generation and load consumption and to calculate on this basis an operation/scheduling program for the local battery. This system is further able to connect devices of different manufacturers. This is an important advantage as FLEXGRID does not have to deal with a variety of proprietary communication standards of devices on the lower house level. Instead, FLEXGRID can focus solely on connecting to the Sunny Home Manager as the lower energy management authority and this device deals with the control of all local home devices.

Main target of the system is to maximize self-sufficiency of the customer and at the same way to minimize the energy consumption from the grid, as the tariffs for residential customers are nearly three times as high as the production costs from the own PV-system. However, the optimization algorithm in the Sunny Home Manager focuses only on the local building. A connection to a superior optimization level is not realized right now and this is where FLEXGRID intelligence steps in and what the specific pilot test case will deal with.

Prosumers increasing their self-sufficiency become highly unpredictable in terms of time and height of feed-in power and consumed power. The pilot test sites implement a test setup that still increase self-sufficiency, but follow strict guidelines given by the local DSO (i.e. bnNETZE).

Exactly at this point, BADENOVA and SMA want to create an additional benefit for the DSO as well as for the private customer by connecting the households to a superior entity (e.g. FLEXGRID ATP) and thus making the flexibility potential accessible to the DSO (i.e. bnNETZE). The private household still optimizes its own consumption via the local Home Manager most time of the day and can offer auxiliary services to the DSO in dedicated time slots, participating in a large-scale community. This approach seems to be technically feasible, as many battery storages on household level are dimensioned too big and still hold capacity-reserves, which are not used. Figure 19 illustrates the approach.

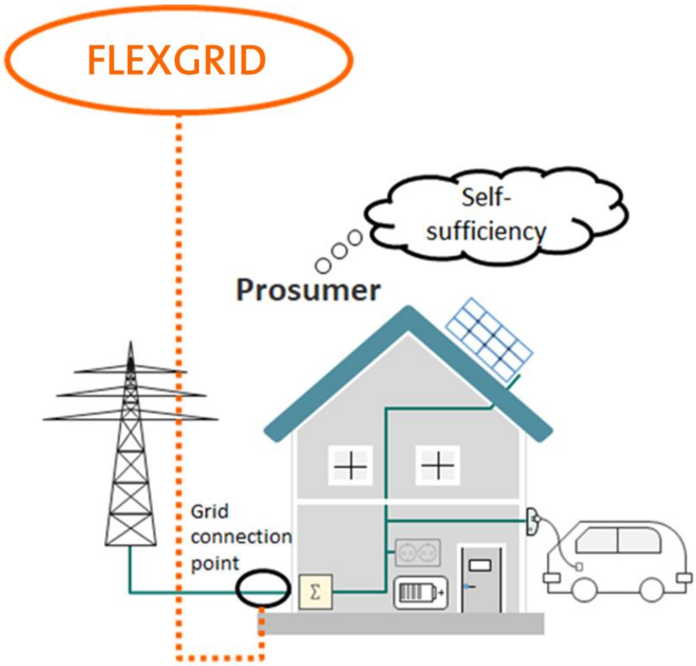

Figure 19: Added value for private customers with home management system

Technical data of participating prosumers:

- **PV-Panels/Inverter:** PV-Panels and the corresponding inverters are already installed. The PV-systems are in a power range between 5 and 10 kWp with different manufacturers of the modules. All inverters originate from SMA, but different models are installed.
- **Home Management System:** All pilot test sites for DES will use the Sunny Home Manager 2.0 from SMA that enables an efficient use of solar energy as well as control of battery storages, wall boxes for EV charging and household appliances (Figure 20). In addition, the Sunny Home Manager is open for connecting devices from other manufacturers. A list of compatible devices is available. All Sunny Home Managers are installed with the version 2.0. It will yet only be the subordinate control device on house level that executes additionally requests of the superior control level made available via the communication gateway.

Figure 20: Sunny Home Manager 2.0 [SMA21]

- **Storage systems:** The distributed energy storage systems are already installed in each household. As battery inverters devices from SMA are used in all cases. The batteries themselves are quite different:
    - Manufacturer (LG, Sony, BMZ, BYD…)
    - Year of production (2015 – 2020)
    - Capacity (2 – 20 kWh)
    - Power (2,5 – 4,6 kW)
- **Charging stations:** In two households, charging stations for EVs are installed. They are compatible to the Sunny Home Manager and controllable via this device.

4.3.2 Setup plan

FLEXGRID can provide an additional value to take over the role of a superior management authority on an upper level. This implies taking into consideration the needs of superordinate interests and creating additional revenues by using new business models. A strong effort is set on the financial assessment of the flexibility potential as well as the scalability of the approach after closure of the project FLEXGRID, if the business idea has passed the proof of concept.

The following Figure 21 illustrates the setup and communication for the participating customers with DES. The detailed plan for the data flow is as follows: The DSO/flexibility operator sends commands to the FLEXGRID platform, if flexibility is required. Flexibility requests will always be limited to a certain time frame. The FLEXGRID platform then enables the DSO to use the flexibility potential of the DES. FLEXGRID directly transfers control requests to a newly developed product of SMA, a communication gateway, which will be installed next to the already existing Sunny Home Manager acting as the local control unit. In all participating customer households, these gateways will be installed. The gateway stands as a communication interface between the FLEXGRID platform and the Sunny Home Manager.

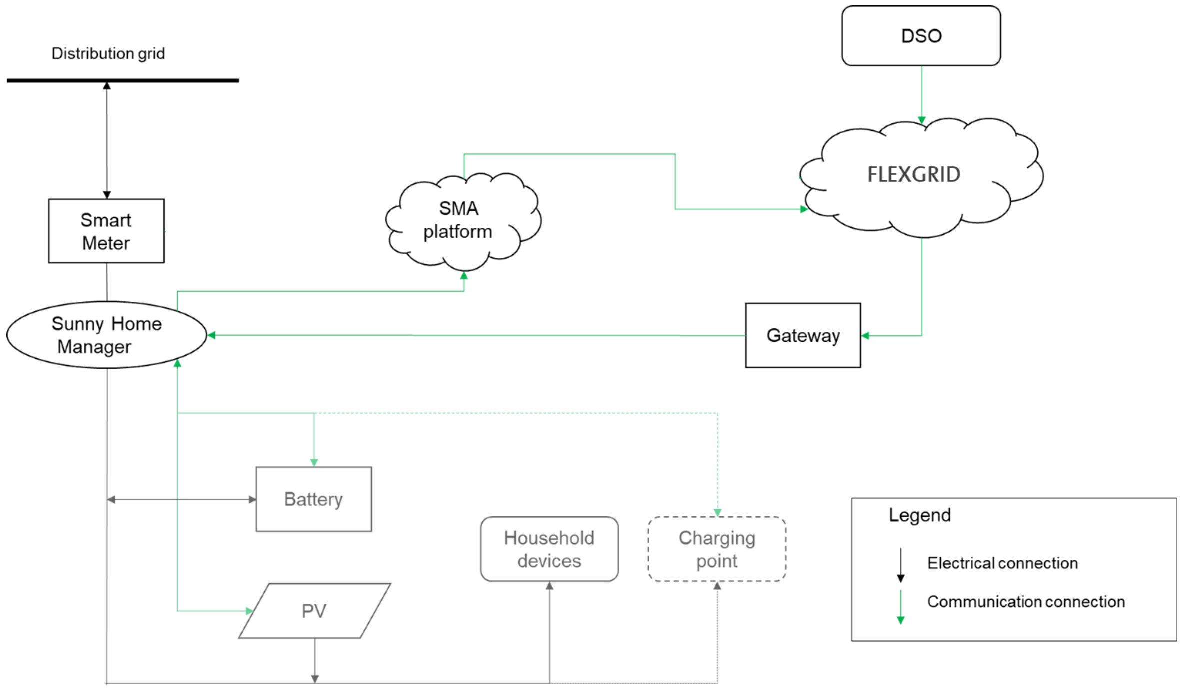

Figure 21: Communication setup plan

Control requests are sent from the FLEXGRID platform to the gateway, which transfers the commands to the Sunny Home Manager finally executing these commands. The additional control requests from the FLEXGRID platform are expected to use the usual time slots of 15-minute intervals for one complete day. The necessary status-information of the devices in the households (PV-systems, battery, maybe wall box for charging an e-vehicle) will be provided via the Sunny Home Manager and an already existing platform – the "SMA Sunny Portal Professional" as well as the dedicated "RESTful Interface". An explicit API description is available, to realize the connection between the SMA Sunny Portal Professional and the FLEXGRID platform.

There are three separate interfaces communicating with the FLEXGRID platform. The platform of the smart meter operator transfers data from the smart meter into the FLEXGRID platform. The cloud platform of SMA transfers data that was initially received by the Sunny Home Manager. The platform of SMA solely stands as a communication interface to the FLEXGRID platform transferring data from the battery, generation, consumption and possibly charging points. Both data streams, which are retrieved by the FLEXGRID platform are read only. Even in this case, the implementation of smart meters is not for sure due to the approval issues already described in the section related to the CES. But information as PV-Generation and local load are provided by the SMA platform too so the FLEXGRID platform will be able to request all needed information.

For the centralized energy storage, the focus lays on a CES offering local services to the grid and on the general needs of the DSO or a flexibility operator. The storage will be used in multi-purpose way:

1) Avoiding grid expansion by using CES (local)
2) Using CES for congestion management and voltage control (local)
3) Peak-shaving for the entire grid (general)

For the distributed energy storage, the focus lays on a new concept that enables additional services of DES, which will be tested within the project. For the test setup, external control and management of the home management system will be enabled in dedicated time slots that change the power limits at the grid connection point.

Setup plan:

1) Control and operation of the DES follows clear guidelines of FLEXGRID platform when flexibility is requested from the DSO or a flexibility operator
2) Idea: There is not a strict value for the charge/discharge power of the battery but a strict limit for the required power at the grid connection point of the participating households.
3) DES deals with volatility of PV-generation and consumption of the household
4) The local home management system controls and optimizes self-efficiency of the participating household when no flexibility is requested by the DSO

Summary of business-related advantages:

- Automatic control and management of energy flow at the grid connection point by the DES via the FLEXGRID platform. An unpredictable customer becomes predictable. This means an important upgrade in customer quality from the perspective of the DSO.

- Enables new end customer services such as variable tariffs, community tariffs, remuneration for grid stability etc. especially when smart meters will be rolled out over Germany in the future.
- Creation of additional value for the participating customers, as the main target of maximising self-sufficiency is not affected in an intolerable manner by the superior level target of reducing peak load costs for the DSO.

5 Evaluating Advanced Market Clearing Algorithms and x-DLFM Architectures

5.1 Overview

5.1.1 Evaluation of the FLEXGRID advanced market architectures

The goals of FLEXGRID are to enable energy sector stakeholders (DSOs, TSOs, aggregators, retailers, energy/flexibility service providers) to: *i)* easily and effectively create advanced ESs, *ii)* interact in a dynamic and efficient way with their environment (electricity grid) and the rest of the stakeholders, and *iii)* automate and optimize the planning and operation of their ESs. In this way, FLEXGRID envisages secure, sustainable, competitive, and affordable ESs. In order to facilitate bottom-up investments, modern smart grids have to cope with the challenging distribution network management. Thus, FLEXGRID develops flexibility market architectures, which allow DSOs to: *a)* integrate – through an open market – Distributed Energy Resources (DER) in a scalable way and, *b)* efficiently interact with all energy sector stakeholders. The different market architectures proposed by FLEXGRID have already been described in detail in [FleD22, FleD51, FleD61]. In this way, several market stakeholders from both FlexDemand (i.e. DSOs/TSOs) and FlexSupply sides will benefit from FLEXGRID services.

FLEXGRID examines in depth the operation of the existing energy markets and the evolution of energy market architectures. Many of the today's changes to the power system are mainly affecting the distribution grids. The main driver here is the integration of more and more RES, which are distributed throughout the medium and low-voltage grids in Europe. However, with the increased shares of DERs, as well as new sources/patterns of demand, such as electric vehicles and more flexible industrial demand, distribution grids are expected to experience increasingly more local congestion and voltage-related problems in the future. To tackle these challenges, there is a need for the DSO to ensure that the local constraints of the distribution grid are integrated into the existing market clearing processes and to become an active buyer of flexibility in a similar way that the TSO does. For this purpose, FLEXGRID have introduced the novel concept of a "Distribution Level Flexibility Market - DLFM", which is operated in an efficient manner by an independent company (e.g. NODES) in collaboration with the DSO [FleD51].

One important aspect of these new DLFM architectures is the development of advanced market clearing algorithms able to adequately model the underlying grid and ensure market efficiency. The project develops innovative Optimal Power Flow (OPF) algorithms and advanced market clearing processes that: *i)* can cope up with uncertainties due to high RES penetration, *ii)* are scalable and multi period so at to make optimal use of Energy Storage Systems (ESS) and Demand Side Management (DSM). These concepts have already been presented in detail in [FleD51].

One of the goals of WP7 is to validate and evaluate the DLFM architectures developed in FLEXGRID. Due to current regulatory limitations and the complexity and novelty of some of these DLFM architectures, they will be tested using realistic simulations and emulations at the AIT SmartEST laboratory at TRL 4. The lab tests of the DLFM architectures have the following two main goals:

- Validation of the different x-DLFM architectures
- Evaluating the x-DLFM architectures against each other and against a baseline scenario
- Evaluation of different possibilities to integrate the x-DLFM architectures into existing markets and existing regulation

The main difference between the two goals is that the first concentrates on validating that the functionality of the DLFM architectures (i.e. advanced market clearing algorithms) operates as intended. On the other hand, the second goal focuses on evaluating the advantages and disadvantages of the different x-DLFM architectures, while the third goal compares different ways that the DLFM architectures can be integrated into existing energy markets and regulation. This will also provide guidelines when (i.e. in which regulatory and policy context) to use the different architectures and when not.

The following section contains an overview of the different DLFM architectures. Later on, in Section 5.2, different validation scenarios are presented that will show how the DLFM architectures will be validated.

5.1.2 Distribution Level Flexibility Market (DLFM) architectures

FLEXGRID proposes three main market architecture variants. The first one acts *reactively* to the existing energy markets and in this way sacrifices efficiency, but on the other hand it is compatible with today's grid and markets' operation. The second one ensures an a-priori feasible dispatch of FlexAssets that reside at the distribution network by proposing a *proactive* distribution network aware market. The third architecture assumes the evolvement of the existing markets (i.e. day ahead energy market, day-ahead reserve market and near-real-time balancing energy market) but offers the maximum possible smart grid efficiency by maximizing the system's social welfare and thus bringing benefits for all involved actors in the smart grid ecosystem [FleD51].

5.1.2.1 Reactive Distribution Level Flexibility Market (R-DLFM) architecture

The objective of the R-DLFM architecture is to be compatible with the existing regulatory framework. This is done by interacting with the existing Wholesale Market (WM), taking the Day-Ahead Dispatch (DAD) as given, and dealing with distribution level imbalances via the proposed DLFM. It is also capable of coping with forecast inaccuracies in energy production and consumption in assets connected to the distribution and transmission network.

The main advantage of the proposed R-DLFM model is that it is compatible with the existing energy market architecture and respective regulatory framework. This is mainly due to the fact that all existing Transmission Network (TN) level market clearing processes remain unaffected and perform in a business-as-usual manner. R-DLFM model may also have several disadvantages that need to be taken into consideration. Firstly, all markets are operating in a sequential manner (i.e. each market takes as input the results of the previous market without being able to change anything in the dispatch schedule that has been decided), so social welfare results are expected to be sub-optimal. Furthermore, no actual TSO-DSO and MO-FMO (Market Operator and Flexibility Market Operator) coordination may take place because the energy resources at TN and Distribution Network (DN) levels are not pooled together. An architectural overview of the R-DLFM is seen in Figure 22.

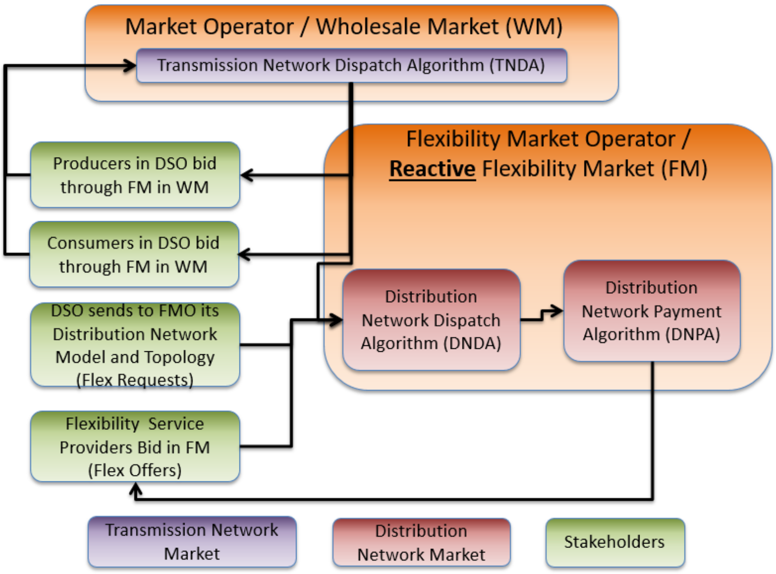

Figure 22: Reactive Distribution Level Flexibility Market (R-DLFM)

5.1.2.2 Proactive Distribution Level Flexibility Market (P-DLFM)

In order to mitigate the drawback of the R-DLFM architecture (which is the difficulty to manage an infeasible or expensive Day-Ahead Dispatch (DAD) of the existing WM), FLEXGRID proposes an optimization of biddings within a distribution network in advance (i.e. proactively) by the FMO. In this way, an a-priori feasible dispatch of the assets that reside in the distribution network is ensured. An overview of such a Proactive-DLFM (P-DLFM) architecture can be seen in Figure 23.

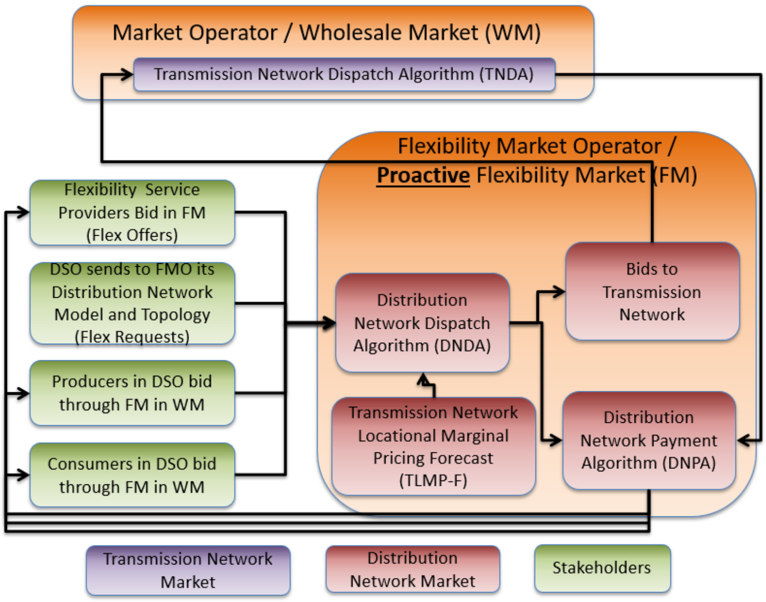

Figure 23: Proactive Distribution Level Flexibility Market (P-DLFM)

The main advantage of P-DLFM model is that DN constraints are taken into consideration in a proactive way. A main drawback is that the TSO may experience high re-dispatch costs, because it can only use the most expensive reserve capacity from the DN-level resources. Another major drawback is that social welfare results may be much worse than optimal, because the proposed dynamic pre-qualification process is based on stochastic RES, consumption modelling and confidence intervals and thus forecast inaccuracies should be taken into consideration.

5.1.2.3 Interactive Distribution Level Flexibility Market (I-DLFM)

Novel smart grid architectures, which are able to maximize social welfare lead to: *i)* energy services with lower cost for consumers, *ii)* more revenue streams for energy producers and Energy/Flexibility Service Providers (ESPs/FSPs), and *iii)* lower operation costs for network/system operators (i.e. TSO and DSOs). In order to achieve this in a smart grid with very high, distributed RES and flexibility penetration, in which distribution network faces congestion and voltage issues, an evolved market architecture though an advanced interaction between TSO and DSO is needed. In this perspective, a new market architecture is needed, that evolves the existing architecture of the wholesale market (day ahead and balancing market) and is not compatible with their existing versions.

Figure 24 presents the Interactive DLFM (I-DLFM) architecture. I-DLFM proposes a market clearing process of a unified energy market, in which stakeholders in both the distribution and the transmission networks can trade energy without causing market imbalances in subsequent markets and network instability problems in other parts of the network. In a nutshell, the core of the proposed market architecture is a unified market clearing based on an iterative process (cf. yellow arrows in the figure below) between the MO (manages the Transmission Network through the operation of the WM) and the FMO (manages the DN according to an innovative flexibility market proposed by FLEXGRID).

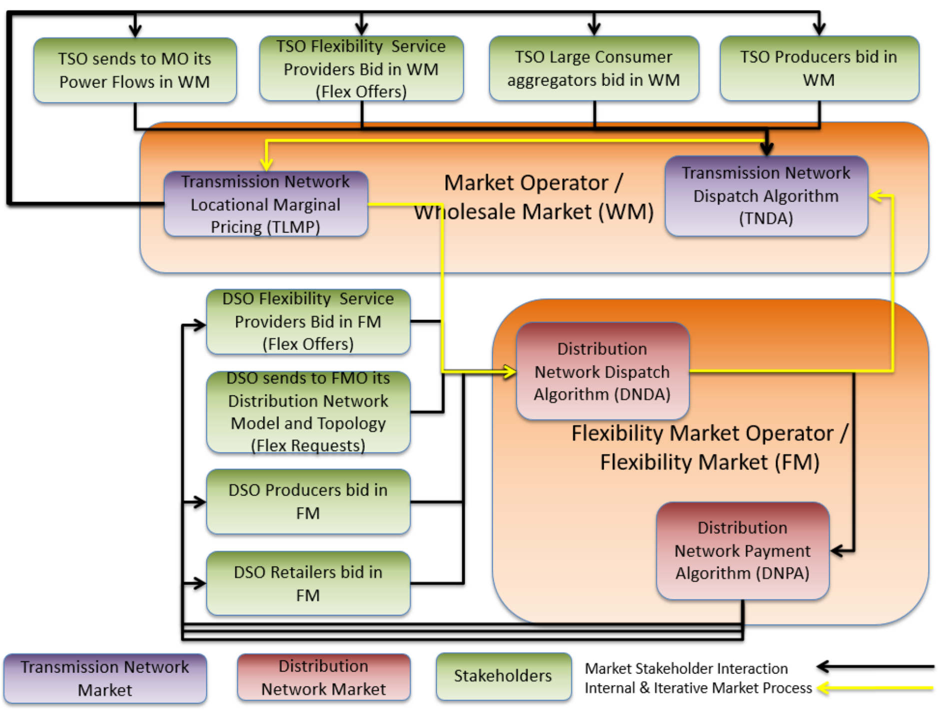

Figure 24: Market based smart grid architecture with optimal social welfare

At each iteration of this process and according to the bids of the transmission network market stakeholders, MO derives a time series (according to the scheduling horizon) of prices (noted as Transmission Network Locational Marginal Prices – TLMPs) for each node in the transmission network. These nodes include the coupling points through which each distribution network exchanges power with the transmission network. FMO of each DSO area takes as input: *i)* TLMPs that MO derived, and *ii)* the bids of the distribution level market stakeholders. In a second step, it derives a time series of power flows (Distribution Network Dispatch – DND) in each node of the distribution network and updates the coupling point power flow time series. The termination condition of this iterative process is an identical dispatch in the transmission and in the distribution networks in two consecutive iterations. According to the final dispatch, the pricing in the transmission network is done with the existing pricing policy in today's smart grids (TLMPs) and the pricing in the distribution network is done through a payment algorithm that the FMO executes.

A main advantage of I-DLFM model is that it can maximize the social welfare and thus provide optimal network operation and market efficiency outcomes. Moreover, the proposed model adopts a decentralized scheme (via the use of decomposition algorithms), which can achieve results similar or very close to the ideal case of a centralized optimization market model. Moreover, it can also be a practical and scalable solution as the complex MO-FMO and/or TSO-DSO coordination problem is decomposed in sub-problems, which can be solved more easily and within the timing constraints set by the regulatory framework and today's real business. One of the main drawbacks of the proposed I-DLFM model is that it is incompatible with the existing regulatory framework and assumes several advancements regarding the Information and Communication Technology (ICT) infrastructure needed to support the proposed advanced coordination schemes.

5.2 Validation scenarios

The validation scenarios for the lab tests are split into two kinds of scenarios. The first kind of scenarios cover the setup of the simulation environment for the different x-DLFM architectures. In the second group, there are scenarios that cover the validation and the evaluation of the x-DLFM architectures.

5.2.1 VS 3.1: No-DLFM scenario for simulation setup validation

This scenario has two main goals. The first goal is the creation and implementation of a flexible simulation setup capable of simulating the different x-DLFM architectures using different scenarios and KPIs. The second goal is to validate the setup using a so called no-DLFM architecture as a basis. The no-DLFM architecture is a representation of the today's market architecture, thus containing no flexibility market at the distribution network level. Once the simulation setup is implemented and validated using the no-DLFM architecture, the setup will be extended to allow validations of the R-DLFM and the P-DLFM architectures in following validation scenarios.

The simulation setup needs to be able to simulate the different x-DLFM architectures and it must be configurable in an automatic manner. An overview of the intended simulation setup is seen in Figure 25. It has two main simulation components. One for simulation of the power system, which will be based on PowerFactory, but may also use real-time simulation systems if needed, such as from Opal-RT. The second simulation component is dedicated to the simulation of the x-DLFM architectures. On top of these two simulation components, there is a simulation coordination layer that will be used to coordinate the simulations. The top layer is an automation layer that is responsible for automatic execution of scenarios and evaluation of KPIs. These layers will be mainly used for VS 3.3 (see Section 5.2.3).

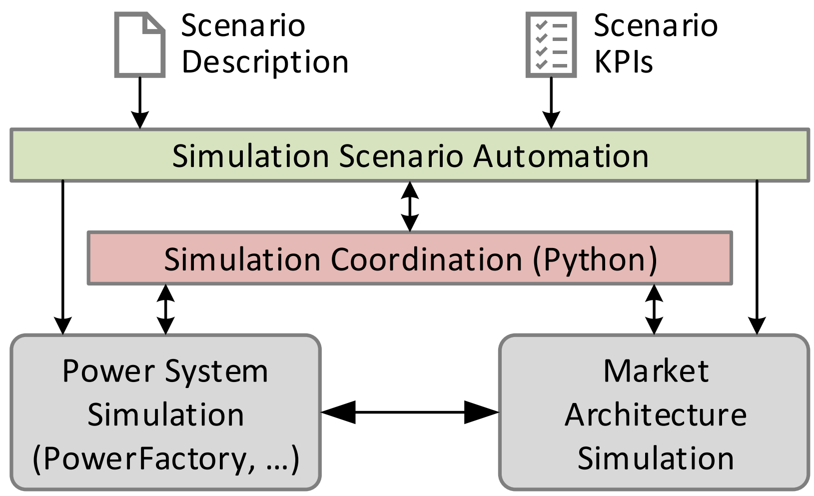

Figure 25: General simulation setup for the lab tests

The simulation setup will first be validated using a no-DLFM architecture. Based on the expertise of Nord Pool Consulting, as a partner of FLEXGRID, the following assumptions were made:

- The MO (e.g. Nord Pool) operates day-ahead and intra-day energy markets at the TN level.
- The FMO (e.g. NODES) operates day-ahead and intra-day energy markets at the DN level. This entity may also be called Local Market Operator (LMO).
- The TSO operates the day-ahead reserve and balancing energy markets at the TN level.
- The DSO operates the day-ahead reserve and balancing energy markets at the DN level.

Within the FLEXGRID project, we assume the sequence of the 3 following markets: *i)* day-ahead energy market, *ii)* day-ahead reserve market, and *iii)* near-real-time balancing energy market. Finally, we assume that this sequence of 3 markets may also take place for the distribution network level. In the sequence diagram in Figure 26, the baseline architecture that represents the today's regulatory framework (i.e. without any DLFM) is illustrated. In the horizontal axis, all basic energy market stakeholders are depicted, namely:

- Market Operator (MO)
- Transmission System Operator (TSO)
- Energy Service Provider (ESP) that uses the FLEXGRID's FlexSupplier's Toolkit (FST) services
- Aggregator that uses the FLEXGRID's Automated Flexibility Aggregation Toolkit (AFAT) services
- Flexibility Market Operator (FMO) that uses the FLEXGRID's Flexibility Market Clearing Toolkit (FMCT) services

- Distribution System Operator (DSO) that uses the FLEXGRID's FMCT services

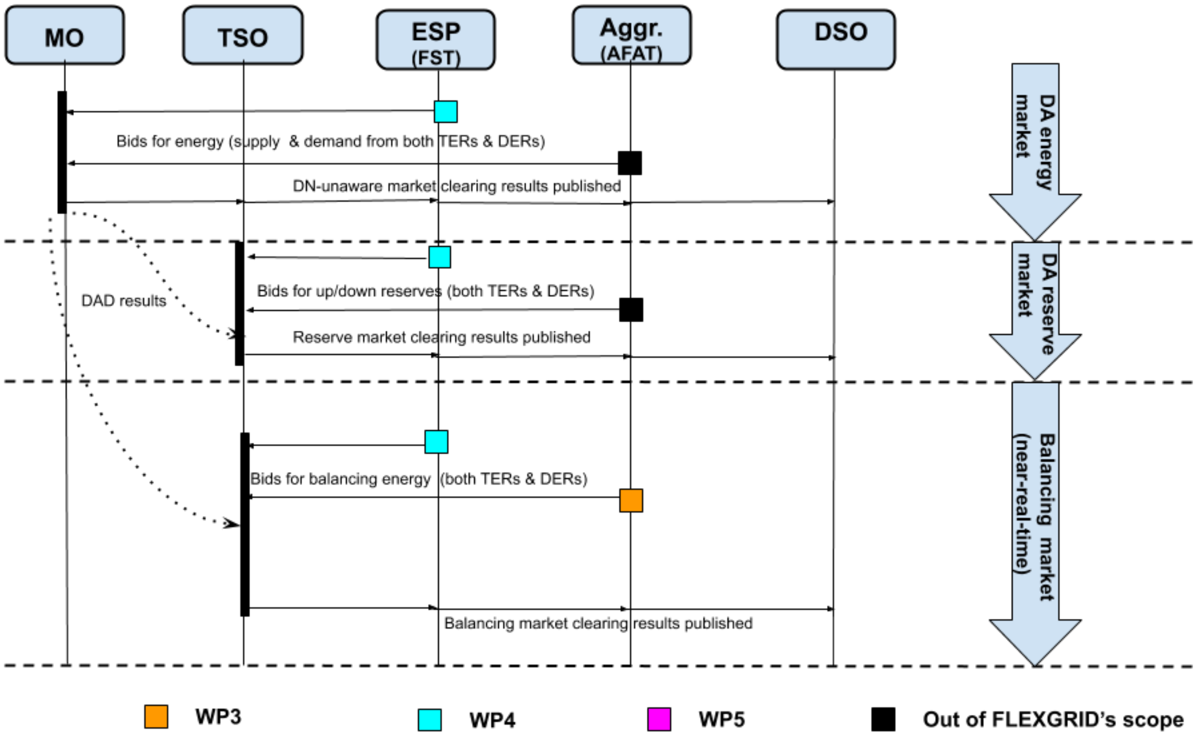

Figure 26: No-DLFM architecture representing the today's EU regulatory framework

In the vertical axis, the temporal sequence of markets is illustrated. For example, in the no-DLFM architecture, where there exist no distribution-level markets, we assume 3 main markets, while in Reactive DLFM architecture, we assume one more market (i.e. DLFM), which takes place after the day-ahead energy and reserve markets and before the near-real-time balancing market.

There are also several coloured boxes, which represent mathematical models and algorithmic solutions that were developed within the FLEXGRID project. For the simulations and lab tests, these will be used when possible and appropriate. The black boxes represent algorithms and processes outside of FLEXGRID's scope. Thus, for the simulations and tests state-of-the-art solutions and algorithms will be used for these parts. Here, the goal is to use as-simple-as possible solutions that will affect the performance of the FLEXGRID algorithms as little as possible. The dotted arrows represent the results from one process, which are communicated to another market actor in order to serve as an input to another process.

5.2.2 VS 3.2: Validation of the R-DLFM and the P-DLFM architectures

The main goal of this scenario is to validate the implementation of the R-DLFM and P-DLFM architectures into the simulation setup. This will be an extension of the no-DLFM scenario used in VS 3.1.

The R-DLFM architecture is described in detail in [FleD61]. Its main advantage is that it is compatible with the existing EU regulatory framework. In Figure 27, the R-DLFM processes are illustrated. Compared to the no-DLFM architecture seen in Figure 26, the R-DLFM contains a section for the flexibility market operation at the distribution level. This section starts with an algorithm that dynamically generates a FlexRequest for the DSO user. This

FlexRequest is a price vs. quantity curve for a given timeframe that represents the various price/quantity tuples that the DSO requests for a flexibility service in order to be able to deal with imminent local congestion and voltage control issues in its distribution network. The elongated purple box represents the market clearing process (auction-based or pay-as-bid) that should be run by the FMO. This market clearing process tries to match the DSO's FlexRequests with the FlexOffers made by the ESPs and aggregators. This can be done via two main algorithms, namely: *i)* auction-based market clearing (i.e. the algorithm runs once after the gate closure), and *ii)* pay-as-bid continuous market clearing. The lab validations and the simulations in WP7 will mainly concentrate on option (*i)*, namely the auction-based market clearing.

We also assume that DAD results have already been published by the MO, so the energy "positions" of all players are known and thus are used as inputs to the FMO's network-aware market clearing algorithm. Another important assumption is that the DLFM clearing results are used as input for the clearing of the near-real-time balancing market operated by the TSO.

For the R-DLFM, the first goal of this validation scenario will be to validate the functionality of the DLFM market clearing process together with the processes already available in the no-DLFM.

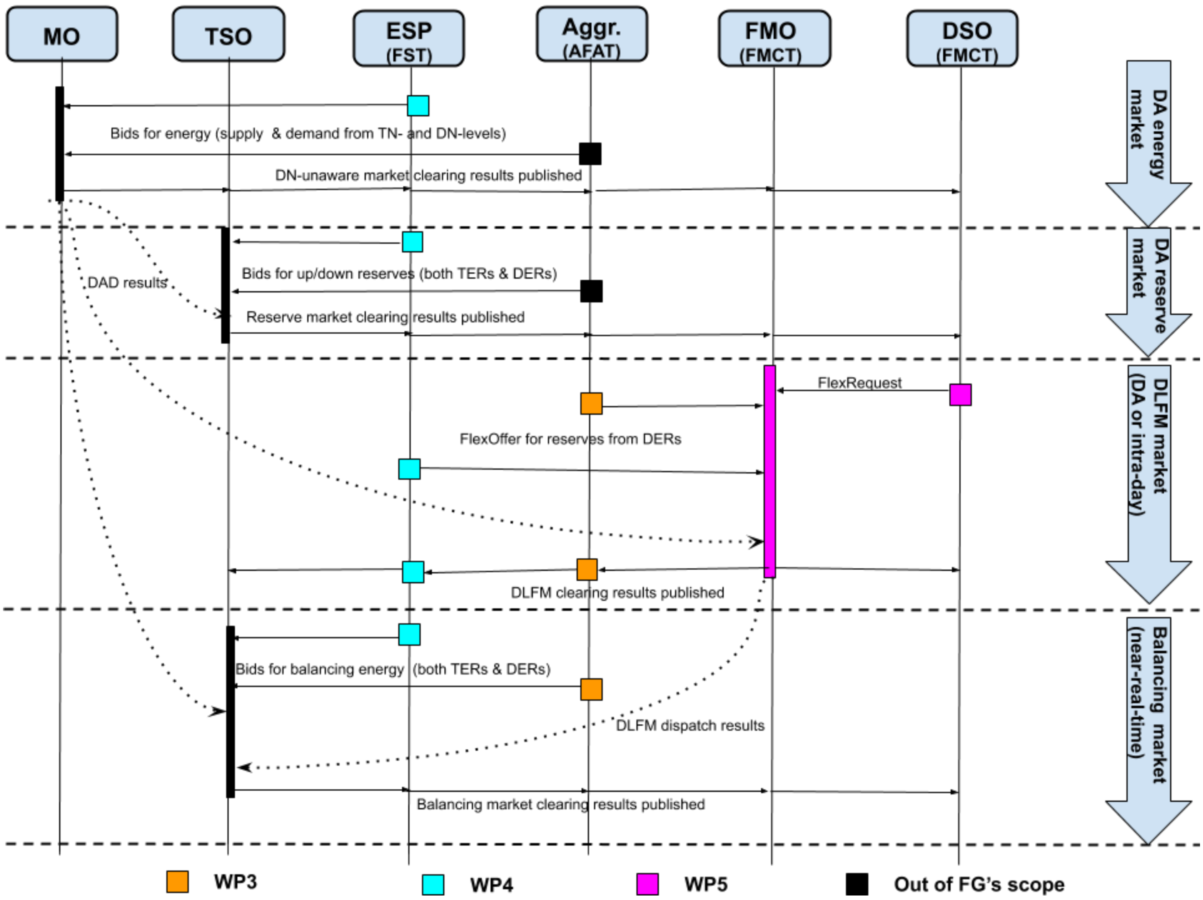

Figure 27: Reactive DLFM architecture (DLFM follows Day Ahead (DA) Energy Market (EM) and DA Reserve Market (RM))

The second goal of this validation scenario is related to the Proactive-DLFM (P-DLFM) architecture, which is also described in detail in [FleD61]. The basic characteristic of P-DLFM is that DN level markets are cleared before the TN-level markets, so the 3 types of DLFMs operate proactively and thus based on their results, the TN-level markets follow. This process can also be seen as a “DN feasibility check” in order to mitigate the main drawback of the aforementioned R-DLFM model, which is the difficulty to manage an infeasible or expensive TN-level dispatch schedule. For the P-DLFM it is assumed that:

- A Day-Ahead Distribution Level Energy Market (DA-DLEM) takes place before the existing DA energy market (transmission level)
- A near-real-time balancing market at distribution network level that takes place right before the existing balancing market operated by the TSO

The P-DLFM sequence diagram is illustrated in Figure 28. Regarding the DLFM clearing process (cf. two long purple boxes), the major difference compared to R-DLFM architecture is that the energy product is traded and not up/down reserve products.

The first goal related to the P-DLFM will be to implement the architecture into the simulation setup seen in Figure 25.

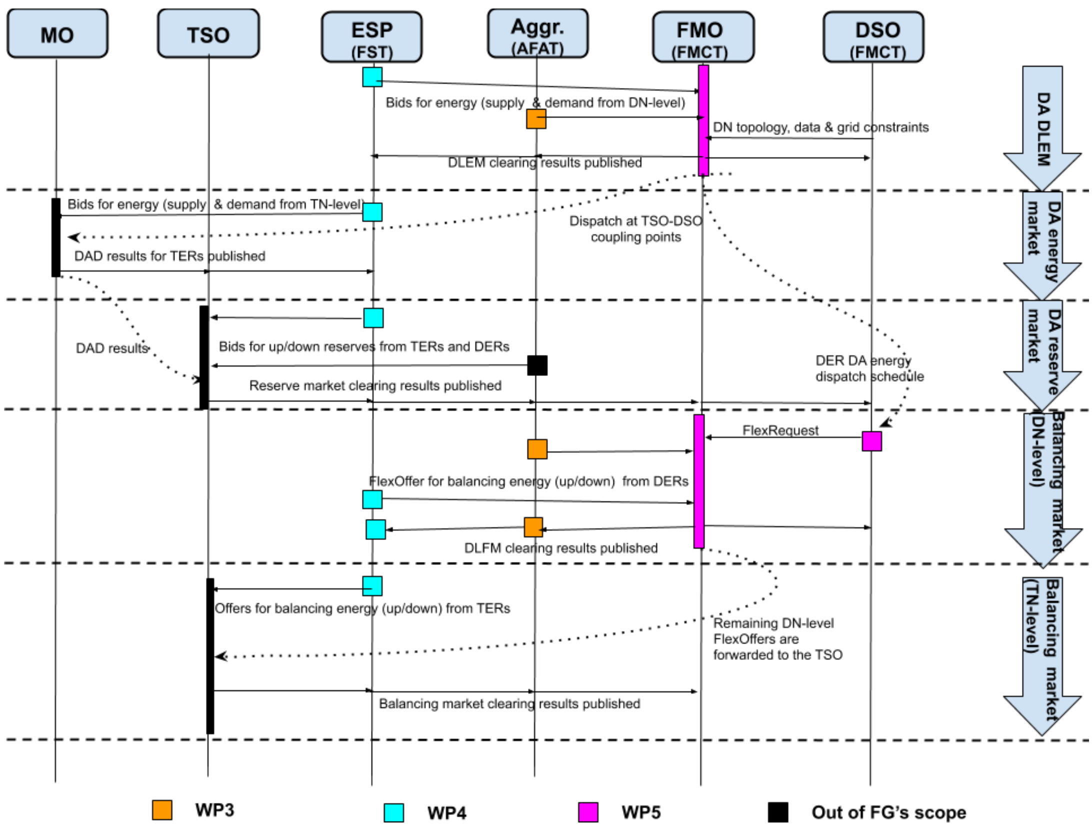

Figure 28: Proactive DLFM (DLFM precedes DA-EM and DA-RM)

5.2.3 VS 3.3: Evaluation of DLFM architectures with varying test conditions

In this scenario, the x-DLFM architectures will be evaluated using multiple test cases and multiple KPIs. In a first step, the simulation setup will be extended to allow fast replication and iteration of simulations using different cases and KPIs. In the second step, the goal is to run multiple simulations of the different DLFM architectures using and combining different test cases and KPIs. The idea is to produce results that show not only when the different DLFM architectures have their advantages but also show their disadvantages. Furthermore, the end goal of this scenario is also to compare the different DLFM architectures with each other and with the no-DLFM case.

Several Use-Case-Scenarios (UCS) have already been defined in FLEXGRID [FleD21]. For the lab validations, three UCS are of significant interest:

- *UCS 3.1:* Coordinated voltage/reactive power control either by aggregating flexibility from multiple FlexAssets or through a market-based mechanism
- *UCS 3.2:* TSO-DSO collaboration for coordinated management of aggregated FlexAssets and interaction between networks' and flexibility markets' operation
- *UCS 3.3:* TSO deals with a frequency control problem either by aggregating flexibility from multiple distributed FlexAssets or through a market-based mechanism

These UCS can also be implemented using different scenario setups. The following list is an indication of scenario setups that may be of interest for the simulations of the x-DLFM architectures:

- Various DER/RES penetration levels at DN level (e.g. low vs. medium vs. high)
- Various battery settings and placement (e.g. one large vs. several small batteries)
- Various DER/FlexAsset sizing and siting tests (i.e. capacity and placing)
- Various DN topology settings
- Various mix of local load/RES profiles
- Various TSO/DSO coupling point cases (i.e. various power injection/absorption cases)
- Various DLFM liquidity scenarios (including results with no adequate local flexibility)
- Compare obligatory vs. market-based re-dispatch scenarios
- Compare DN-aware vs. DN-unaware market clearing algorithms
- Scenarios for DER services' prioritization: priority to TSO or DSO services?
- Various DER/RES forecast inaccuracy scenarios

For these UCS and scenario setups, different KPIs may also be of interest, as indicated in the following list:

- Voltage deviations (e.g. number of times that voltage limit violations occurred)
- Local congestions (e.g. number of times that local congestions occurred)
- Flexibility cost at both TN- and DN-levels (individually) and system as a whole
- TSO's and DSO's balancing/re-dispatch costs
- Social welfare (sum of profits/losses from each participating market player)
- Increased RES/DER hosting capacity
- Reduced energy curtailment of RES/DER (even assume zero RES curtailments)
- Increased hosting capacity for Electric Vehicles and other new types of loads
- Minimum investment on new FlexAssets at the DN level that is needed to retain various probabilistic System Adequacy Index (SAI) factors within acceptable limits
- Improved competitiveness of the electricity market (cf. market liquidity)
- DSO's CAPEX for network upgrades/reinforcement vs. OPEX for purchasing FlexServices (e.g. for the next few years)

In order to cover as many of these UCS with different scenario setups, test automation support will be required. In this validation scenario, the AIT Engineering and Validation

Support System (EVSS) will be used for this purpose (seen in Figure 29). The AIT EVSS allows rapid generation of test configurations and setups for the AIT SmartEST lab [Prö17].

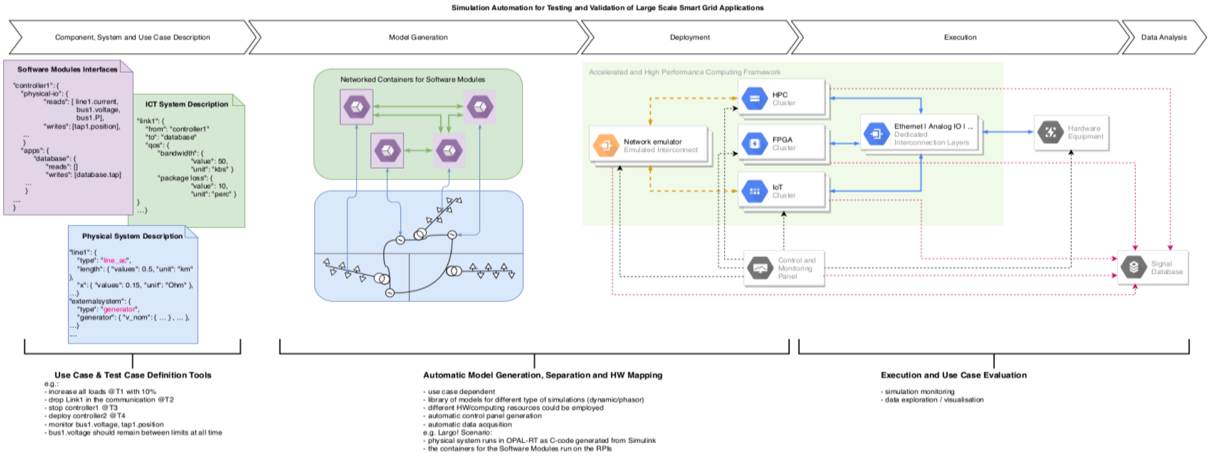

Figure 29: AIT Engineering and Validation Support System for automated testing

5.2.4 VS 3.4: Simulation setup validation of the I-DLFM

This scenario has the goal of extending the base simulation setup to also allow simulation of the I-DLFM architecture. The goal here is to achieve a simulation setup that can be used to realistically simulate this DLFM architecture. The scenario will also contain initial comparisons with the other DLFM architectures.

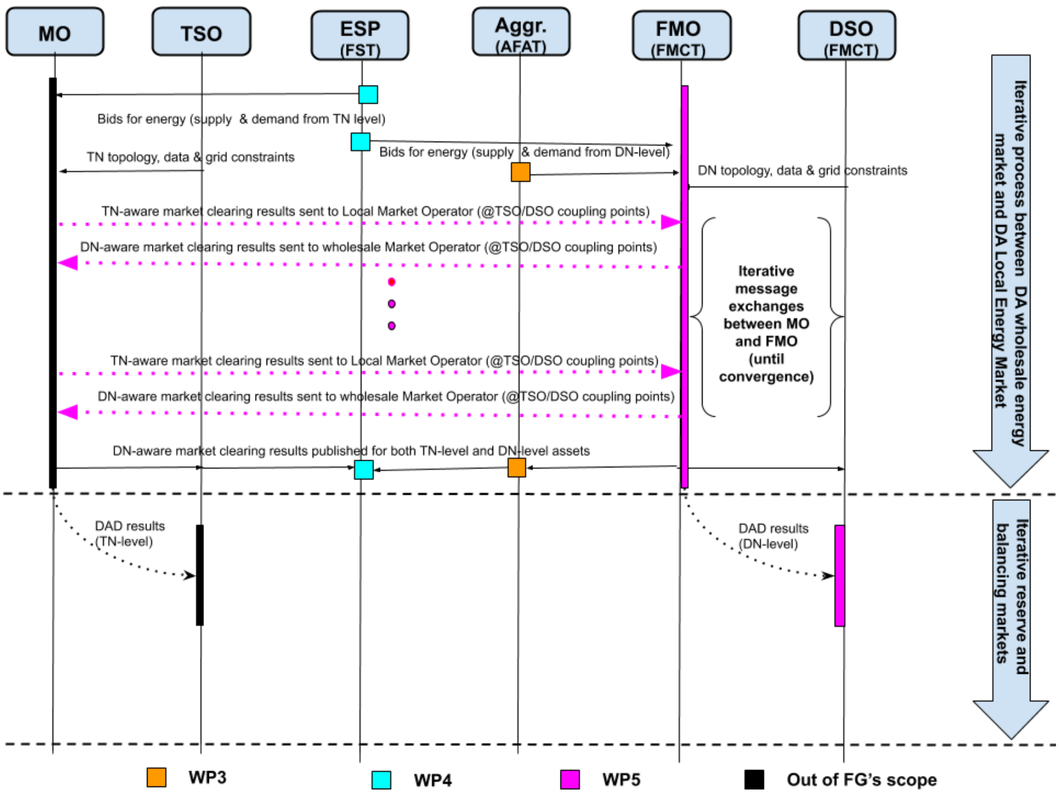

Figure 30: Interactive DLEM (iterative message exchanges between MO and FMO until convergence)

In the I-DLFM architecture model, we consider an iterative process that takes place between the MO and FMO and between TSO and DSO until they converge to an optimal dispatch schedule for both TN and DN levels. In Figure 30 and Figure 31, the sequence diagrams for the MO-FMO coordination and TSO-DSO coordination are illustrated.

As shown in Figure 30, in the day-ahead energy market context, the MO initially runs an instance of its market clearing problem at the TN level and sends the results to the FMO. Then, the FMO takes as input the MO's results and runs its own market clearing problem at the DN level. The respective results (e.g. Lagrange multipliers) are sent back to the MO, who runs another round of the TN-level market clearing. Of course, the dispatch schedules that are decided in each round of algorithm's execution are virtual and are not actuated in reality. After several algorithmic iterations (i.e. several message exchanges between MO and FMO), the process converges to an overall dispatch schedule (i.e. at both TN and DN levels) that maximizes the social welfare.

A similar iterative process shown in Figure 31 may take place for day-ahead reserve markets and near-real-time balancing markets. We assume that day-ahead energy dispatch results are sent by the MO to the TSO and by the FMO to DSO.

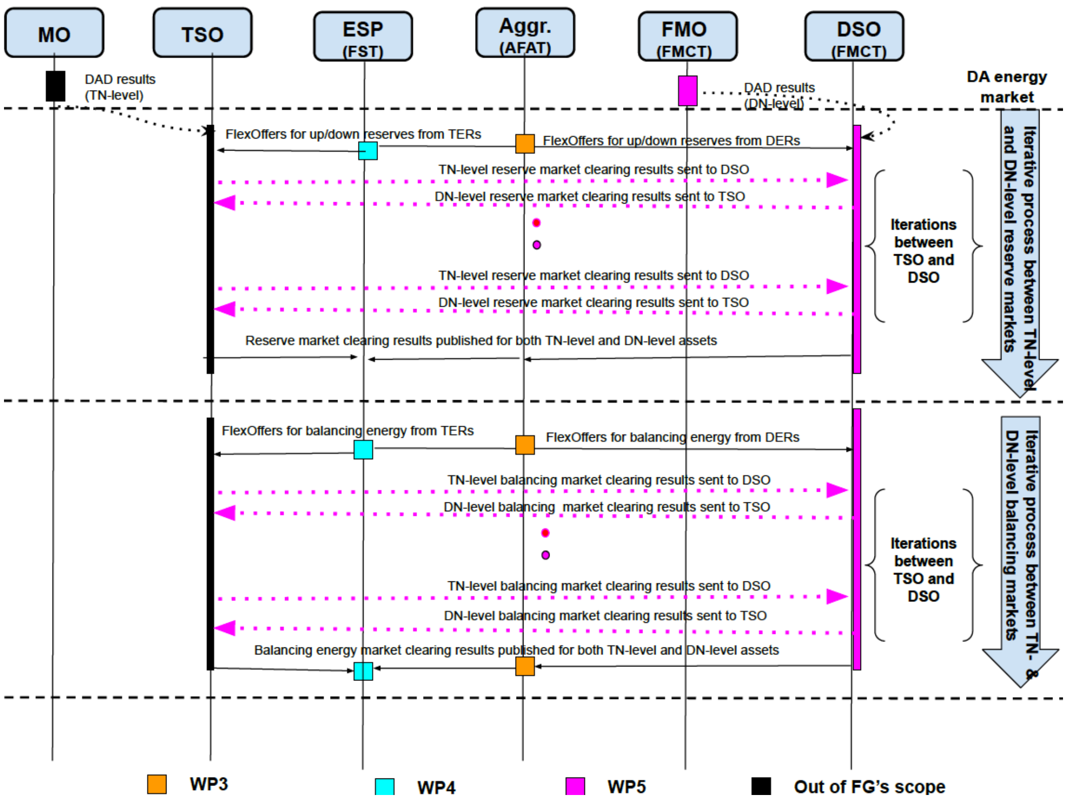

Figure 31: Interactive DLFM (iterative message exchanges between TSO and DSO until convergence)

I-DLFM is quite futuristic approach and is also incompatible with the existing EU regulation, even though it can theoretically achieve better social welfare results. It is currently under development in the FLEXGRID project with theoretical experiments at TRL 3 performed in WP5. Once initial validations have been performed, the lab validations will extend these with more realistic tests at TRL 4.

5.2.5 Initial validation plan

The initial validation plan for the lab tests at the AIT SmartEST lab is seen in Figure 32. The implementation of VS 3.1 has already started. This is the scenario that sets the necessary basis for all the following validation scenarios. It is estimated that this validation scenario will end, and the simulation setup will be ready at the end of June 2021 (i.e. Month 21). This will be directly continued by VS 3.2, where the R-DLFM and the P-DLFM architectures will be implemented and validated. The two following validation scenarios will be partly carried out in parallel. Once first versions of the R-DFLM and the P-DLFM are implemented, VS 3.4 can be started, where the I-DFLM will be implemented and validated. At the same time, VS 3.3 will also be carried out. This is the main scenario where most results are expected. Once the I-DLFM has been implemented, it will also be evaluated in VS 3.3.

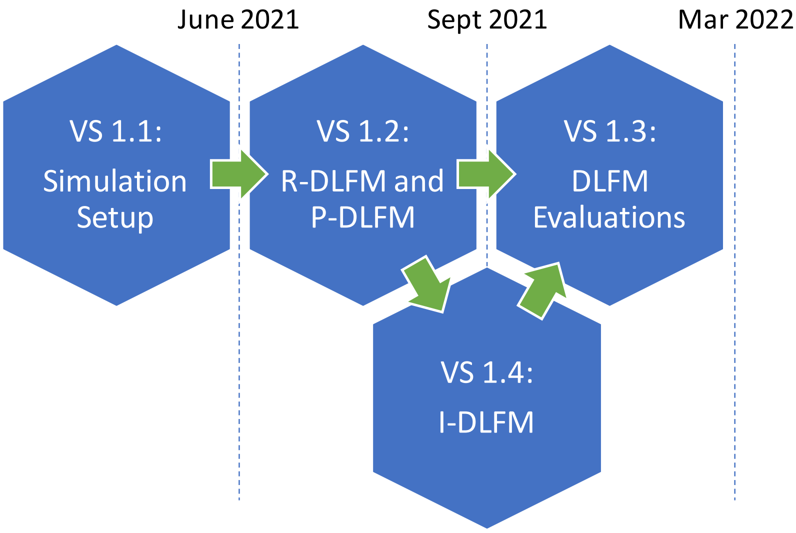

Figure 32: Validation plan for the simulations at the AIT SmartEST lab

5.3 Lab environment and setup plan

5.3.1 Laboratory setup

5.3.1.1 Overview of the AIT SmartEST laboratory

The AIT SmartEST laboratory infrastructure offers an environment for testing, verification and R&D in the field of large-scale distributed energy system integration and Smart Grids applications. The infrastructure accommodates DER components, such as inverters, storage systems, Combined Heat and Power (CHP) units, voltage regulators/controllers, and other types of related electrical equipment. Powerful controllable AC and DC sources allow full-power testing capability up to 1 MVA (AC), including a high-performance PV Array (DC) Simulation and bidirectional source/sink for battery emulation. Additional equipment for simulating control and communication interfaces and the possibility of operating the equipment under defined (extreme) temperature/humidity conditions offer extended testing capabilities [Bru15].

Advanced power system experiment and verification methods available at the lab include real-time (RT) Power Hardware-In-the-Loop (PHIL) simulation combining close-to-reality hardware system tests with the advantages of numerical simulation to allow for the integration of battery models into the laboratory analysis. By means of a controllable AC voltage source distribution network models can be coupled to the real components to develop, validate and evaluate control algorithms, system concepts and components for Smart Grid applications.

Figure 33 shows a simplified schematic of the AIT SmartEST lab. Designed as a pure low voltage (LV) (400 V) lab, all AC buses are rated for operation at voltages up to 480 V (line-to-line). The laboratory itself is supplied from the local 20 kV medium voltage (MV) grid via two independent MV/LV transformers. The following infrastructure is available in the SmartEST lab:

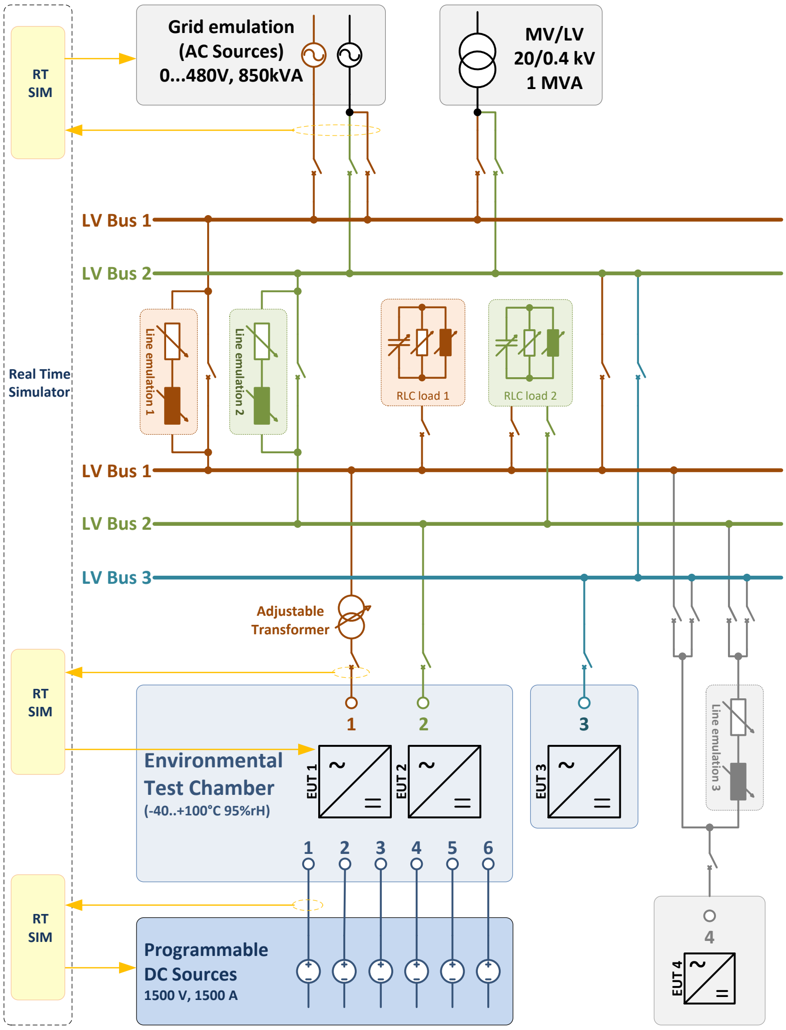

Figure 33: Simplified schematic of the SmartEST laboratory.

Electrical setup and components:

- Grid simulation (3 independent laboratory grids; 2 independent high bandwidth grid simulators—0-480 V, 800 kVA; 3-phase balanced or unbalanced operation; LVRT/FRT testing possibilities)
- Line impedance emulation (adjustable line impedances for various LV network topologies: meshed, radial or ring network configuration)
- Adjustable loads for active and reactive power (freely adjustable RLC loads up to 1 MW, 1 MVAr—capacitive and inductive behaviour; individual control possibilities)

- Environmental simulation (test chamber for performance and accelerated lifetime testing)
- DC sources (6 independent dynamic PV array simulators: 1500 V, 1500 A, 960 kVA)
- DAQ and measurement (multiple high precision power analysers with high acquisition rate; simultaneous sampling of asynchronous multi-domain data input)

Simulation tools and components:

- Multicore Opal-RT Real-Time Simulator (i.e., eMegaSim)
- Typhoon HIL Real-Time HIL Simulator
- Mathworks xPC-Target Simulator
- PHIL and CHIL experiments at full power in a closed control loop
- General simulation tools: Matlab / Simulink, SimPowerSystems, PSpice / Cadence
- Network simulation tools: DigSILENT PowerFactory, NEPLAN, PSAT
- Communication network simulator: Omnet++
- Powerful simulation cluster for complex and large-scale system simulations (incl. co-simulation power system and information and communication/automation infrastructure)

ICT/Automation tools and components:

- SCADA and automations system (highly customizable laboratory automation system, remote control possibilities of laboratory components, visualization and monitoring)
- Distributed control approaches: IEC 61499 / 4DIAC
- Communication methods: IEC 61850, OPC/OPC-UA, Industrial Ethernet (Ethernet Powerlink, Modbus / TCP, etc.)
- Planning methods, interoperability and compatibility, integration: IEC 61970 / 61968 (CIM)
- Network information system
- Cyber-security assessment methods and tools for Smart Grid systems and components

5.3.1.2 Interfacing using the AIT Lablink

When developing novel power grid components and solutions, testing those solutions efficiently can be challenging. Especially connecting a newly developed solution to existing hardware and software for testing purposes proves to be difficult. AIT Lablink is a communication middleware that allows quick and easy coupling of software and hardware components. The core of the AIT Lablink is free and can be provided to partners for incorporation into their tools and applications. This allows for easy access to the AIT SmartEST lab once on-site at AIT.

Several AIT Lablink clients have already been developed. Examples are clients for DIgSILENT PowerFactory®, OMNeT++, Electric Vehicle (EV) simulators and OPAL-RT. Using AIT Lablink, it intended to be a door-opener to the rich-equipped AIT SmartEST laboratory and the available AIT Lablink-enabled components.

5.3.2 Setup plan

The setup needed is mainly limited to setting up the simulation environment, as described in VS 3.1 (see Section 5.2.1). However, due to the already existing interfacing possibilities in the SmartEST lab (i.e., the AIT Lablink), the integration of the x-DLFM architectures together with the simulators should be straightforward and not require an additional setup plan.

If the simulations need to be extended with additional hardware or components, this can also easily be done without special consideration or planning. Again, the AIT Lablink was developed for such cases and allows rapid switching between pure simulations and Hardware-In-the-Loop (HIL) cases.

6 Conclusions and Next Steps

The goal of FLEXGRID is to facilitate energy sector stakeholders to easily and effectively create advanced ESs, interact in a dynamic and efficient way with their environment (electricity grid) and the remaining of the stakeholders, and automate and optimize the planning and the operation of their ESs. These goals will be fulfilled in FLEXGRID by the development of a service oriented smart grid architecture that offer energy stakeholders several tools equipped with mathematical models and algorithms that allow optimal planning and operation.

In order to validate these methods and tools, three validation strands were defined and analytically described in this report. The first two strands are pilots to study the benefits of the FLEXGRID tools from different perspectives. The first pilot strand is related to automated energy flexibility aggregation as a service for ESPs and aggregators. The second pilot strand will evaluate the FLEXGRID ATP's forecasting methods and how they can be applied for novel DSO services' provisioning. The third strand uses realistic simulations in the AIT SmartEST lab and experiments to evaluate the FLEXGRID x-DLFM architectures.

This deliverable presents the current state of the demonstration setup plan, the experimentation plan and validation methodology chosen for the three validation strands. For each strand, selected validation scenarios are presented together with an initial plan for how the scenarios will be validated. Also, a general description of the available test infrastructure is presented.

The first strand is organized by UCY and is carried out at UCY university campus test site. It focuses on evaluating the FLEXGRID tools that can be used for automated energy flexibility aggregation. The focus here is on FLEXGRID tools that can be used by ESPs and aggregators. Three validation scenarios were identified. The first scenario (VS 1.1: Aggregator manages a FlexRequest) is related to "UCS4.1 – An Aggregator efficiently responds to FlexRequests made by TSO/DSO/BRPs by optimally orchestrating its aggregated flexibility portfolio of end energy prosumers". The goal here is to evaluate how an aggregator can use the FLEXGRID tools to optimally manage a FlexRequest. In the second scenario (VS 1.2: Aggregator creates a FlexOffer), the settings are similar but here the goal is to show how the tools can be used to allow an aggregator to efficiently create FlexOffers and automatically submit them in FLEXGRID ATP. The last validation scenario for this pilot is VS 1.3: Extension with Virtual FlexAssets, which extends VS 2.1 and VS 2.2 by adding virtual simulated FlexAssets. The goal here is to run several offline validation scenarios about a hypothetical future installation of more FlexAssets in the UCY campus in order to identify potential economically sustainable green energy investments.

The second strand is organized by bnNETZE and will use their test grid in Freiburg, Germany. The main goal of this pilot is to evaluate FLEXGRID forecasting methods and tools that can be used for DSO services' provisioning. This pilot is divided into three periods, where the first is dedicated to theoretical analysis and simulation of DSO forecasting methods. In the second period, these methods will be incorporated into the real test site. Finally, the third period will be used to validate the methods in the field using the bnNETZE test site. Four validation scenarios were identified, where the first three are focusing on the validation of different forecasting methods (VS 2.1: PV forecast, VS 2.2: Price forecast, and VS 2.3: Load forecast). The fourth scenario (VS 2.4: Peak shaving) is used to take these forecasting methods into the field and use them to enable peak shaving of the entire bnNETZE's distribution grid.

For the third strand, lab tests at the AIT SmartEST lab will be carried out, where the focus is on evaluating advanced market clearing architectures. Here, the x-DLFM architectures developed in the FLEXGRID project will be validated and evaluated. Four validation scenarios were identified, where the first two cover the setup and development of the simulation setup (VS 3.1: No-DLFM scenario for simulation setup validation) and the simulation of the R-DLFM and the P-DFLM architectures (VS 3.2: Validation of the R-DLFM and the P-DLFM architectures). The third validation scenario (VS 3.3: Evaluation of DLFM architectures with varying test conditions) will cover the main evaluations by simulating the different DFLM architectures using different test cases and KPIs. The fourth validation scenario (VS 3.4: Simulation setup validation of the I-DLFM) focuses on the implementation of the I-DLFM architecture and will be carried out in parallel with VS 3.2 and VS 3.3.

The main outcome of this deliverable is the validation scenarios defined for each test activity. These will be the main basis for the further activities of Work Package 7. According to the validation methodology (see Section 2), the next steps will be to select specific test cases based on the validation scenarios. This is followed by a phase of experiment's technical specification, where it is specified in detail how the experiments should be executed and on which equipment. In parallel with these two phases, the test setups need to be further developed by integrating the FLEXGRID tools and methods. The last step in the validation methodology is to carry out the specified experiments and evaluate the results.

7 References

[Bla16] M. Blank, S. Lehnhoff, K. Heussen, D. E. M. Bondy, C. Moyo, and T. Strasser, "Towards a foundation for holistic power system validation and testing," in 2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA), Sept 2016, pp. 1–4.

[Bru15] R. Bründlinger, T. Strasser, G. Lauss, A. Hoke, S. Chakraborty, G. Martin, B. Kroposki, J. Johnson, and E. de Jong, "Lab tests: Verifying that smart grid power converters are truly smart," IEEE Power and Energy Magazine, vol. 13, no. 2, pp. 30–42, March 2015.

[Chai14] Chai, T., and R. R. Draxler. "Root Mean Square Error (RMSE) or Mean Absolute Error (MAE)? – Arguments against Avoiding RMSE in the Literature." *Geoscientific Model Development*, vol. 7, no. 3, 2014, pp. 1247–1250., doi:10.5194/gmd-7-1247-2014.

[ERI21] ERIGrid, "ERIGrid – H2020 Research Infrastructure Project", Mar. 2021, https://erigrid.eu/

[FleD21] FLEXGRID D2.1, "FLEXGRID use case scenarios, requirements' analysis and correlation with innovative models". Available online: https://flexgrid-project.eu/assets/deliverables/FLEXGRID_D2.1_v1.0_31012020.pdf

[FleD22] FLEXGRID D2.2, "The overall FLEXGRID architecture design, high-level model and system specifications". Available online: https://flexgrid-project.eu/assets/deliverables/FLEXGRID_D2.2_final_31032020.pdf

[FleD51] FLEXGRID D5.1, "OPF objectives and challenges towards smart grids with high RES penetration", Available online: https://flexgrid-project.eu/assets/deliverables/FLEXGRID_D5.1_final_03122020.pdf

[FleD61] FLEXGRID D6.1, "Data Model of FLEXGRID architecture".

[FleD81] FLEXGRID D8.1, "Data management, dissemination and exploitation plans". Available online: https://flexgrid-project.eu/assets/deliverables/FLEXGRID_D8.1_final_31032020.pdf

[Hyn18] Hyndman, Rob J, and George Athanasopoulos. "Forecasting: Principles and Practice." OTexts, Apr. 2018.

[Kim18] Kim, Youngjoo, and Hyochoong Bang. "Introduction to Kalman Filter and Its Applications." IntechOpen, IntechOpen, 5 Nov. 2018, www.intechopen.com/books/introduction-and-implementations-of-the-kalman-filter/introduction-to-kalman-filter-and-its-applications.

[Prö17] Pröstl Andrén, F.; Strasser, T.I.; Kastner, W. "Engineering Smart Grids: Applying Model-Driven Development from Use Case Design to Deployment". *Energies* 2017, *10*, 374. https://doi.org/10.3390/en10030374

[SMA21] SMA, "SUNNY HOME MANAGER 2.0", Mar. 2021, https://www.sma.de/produkte/monitoring-control/sunny-home-manager-20.html

[Wer14] Weron, Rafał. "Electricity Price Forecasting: A Review of the State-of-the-Art with a Look into the Future." International Journal of Forecasting, Elsevier, 18 Sept. 2014, www.sciencedirect.com/science/article/pii/S0169207014001083.