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

Report on validation activities of FLEXGRID system and individual research tools

Deliverable D7.2

Document Information

Scheduled delivery	30.06.2022
Actual delivery	04.10.2022
Version	Final
Responsible Partner	AIT

Dissemination Level

PU Public

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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
ATP	Automated Trading Platform
CES	Centralised Energy Storage
DA	Day-Ahead
DAD	Day-Ahead Dispatch
DC	Direct Current
DER	Distributed Energy Resource
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
EES	Electric Energy Storage
ELM	Extreme Learning Machine
EM	Energy Market
ES	Energy Service
ESP	Energy Service Provider
ESS	Energy Storage System
EV	Electric Vehicle
FMO	Flexibility Market Operator
HELM	Holomorphic Embedding Load-Flow Method
ICT	Information and Communication Technology
KPI	Key Performance Indicator
LMO	Local Market Operator
LV	Low Voltage
MO	Market Operator
MV	Medium Voltage
OPF	Optimal Power Flow
PCC	Point of Common Coupling
PV	Photovoltaic
RES	Renewable Energy Sources
RI	Research Infrastructure
R/P/I-DLFM	Reactive/Proactive/Interactive Distribution Level Flexibility Market

RM	Reserve Market
SRA	Scalability and Replicability Analysis
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 7.2. It contains the results from the experiments in WP7 for Validation Strand 3 “Evaluating Advanced Market Clearing Algorithms and x-DLFM Architectures”.

Table 1: Document History Summary

Revision Date	File version	Summary of Changes
21/04/2022	V0.1	Draft ToC circulated among all consortium partners
30/06/2022	V0.1	D7.2 was delayed (almost 3 months) because its contents needed to be enhanced in order to be inter-related with D7.3 (pilot results) and comply with the deadline of Milestone #12 (M36)
29/08/2022	V0.2	Inputs for the replicability study with OPF “Class C”
22/09/2022	V0.3	Inputs for the scalability using LinDistFlow
28/09/2022	V0.4	Draft submitted for review
29/09/2022	V0.5	Comments received from reviewers
04/10/2022	V1.0	Comments addressed and final version submitted

Executive Summary

In order to validate the methods and tools developed in FLEXGRID, three validation strands were developed in the FLEXGRID project, namely: (i) Automated Energy Flexibility Aggregation, (ii) Evaluating Forecasting Methods for DSO Services, and (iii) Evaluating Advanced Market Clearing Algorithms and x-DLFM Architectures.

This deliverable presents the implementation and the results from tests done for the third validation strand, which 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 (TRL 3) and to study different TSO-DSO collaboration possibilities within the scope of the DLFM architectures. The goal with this validation strand is to validate the DLFM architectures using a Scalability and Replicability Analysis (SRA) approach. Due to current regulatory limitations and the complexity and novelty of some of these DLFM architectures, they were tested using realistic simulations at the AIT SmartEST laboratory at TRL 4. The tests of the DLFM architectures have the following main goals:

- To re-implement the DLFM optimization algorithms using a OPF Class C instead of the LinDistFlow solution from previous work (cf. chapter 5 of D7.3)
- Replicability study of the results from WP5
- Scalability study of the DLFM architectures using a realistic distribution system from bnNETZE

The scalability and replicability analysis was performed on the DLFM architectures. Replicability analysis was first performed on the test grids from WP5. These results are comparable to the work performed in WP5. Next, a scalability and replicability study was performed on a real grid from Germany, from the control region of bnNETZE. Here, different scenarios were run using different (i) grid loading constraints, (ii) Electric Energy Storage (EES) penetration and (iii) conventional DG and RES penetration. There is a need for increased cooperation between TSOs and DSOs to tackle the challenges due to climate change and the need for large integration of climate friendly RES generation and electro mobility in future power grids (especially at the distribution network level that FLEXGRID project focuses). Innovative market approaches developed in the FLEXGRID project will help positively the grid and all stakeholders involved.

Secondly, a scalability and replicability analysis was also made based on the convex relaxed mixed-integer linear programming OPF developed in WP5, coupled and validated using a simulation in PowerFactory [DIG22]. Replicability analysis was performed on the IEEE 30-bus system and a real grid from Germany, bnNetze (20 kV) grid. The same approach is applied for three different flexibility scenarios developed with different RES penetrations levels, (i) low, medium and high RES and DG penetration, (ii) low, medium and high flexibility penetration, and (iii) low, medium and high EES penetration. For each scenario, various behaviours of the three x-DLFM market approaches were analysed.

The experiments in this validation strand have proven the scalability and replicability of the proposed DLFM architectures.

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 were developed in the FLEXGRID project: (i) Automated Energy Flexibility Aggregation, (ii) Evaluating Forecasting Methods for DSO Services, and (iii) Evaluating Advanced Market Clearing Algorithms and x-DLFM Architectures. More detailed information about each validation strand can be found in D7.1 [FLED71].

This deliverable presents the implementation and the results from tests done for the third validation strand. 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 #3 has been carried out as simulations and tests in AIT’s SmartEST lab at TRL 4. By validating the DLFM architectures in the lab, it is possible to test scenarios that would not be possible in a realworld pilot, due to market regulations or other limiting factors. 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.

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 and validation activities (Task 7.2), and execution and evaluation of the pilot tests (Task 7.3). This deliverable covers the results from Task 7.2 focusing on the experiments and tests that were developed and executed for the lab validation strand (i.e. TRL 4). The developments and results from the real-life pilot tests (i.e. TRL 5) are presented in D7.3.

1.3 Structure of the document

In Section 1.4, the validation methodology is described. Section 2 contains an overview of the DLFM architectures and the main ideas on how to evaluate them. This is continued with Scalability and Replicability Analysis using two different methods in Section 3 and Section 4. The document is concluded in Section 5.

1.4 Validation Methodology

All validation strands in FLEXGRID follow the same validation methodology. It is based on the ERIGrid Holistic Validation Methodology [Bla16], which is described in more detail below and illustrated in Figure 1.

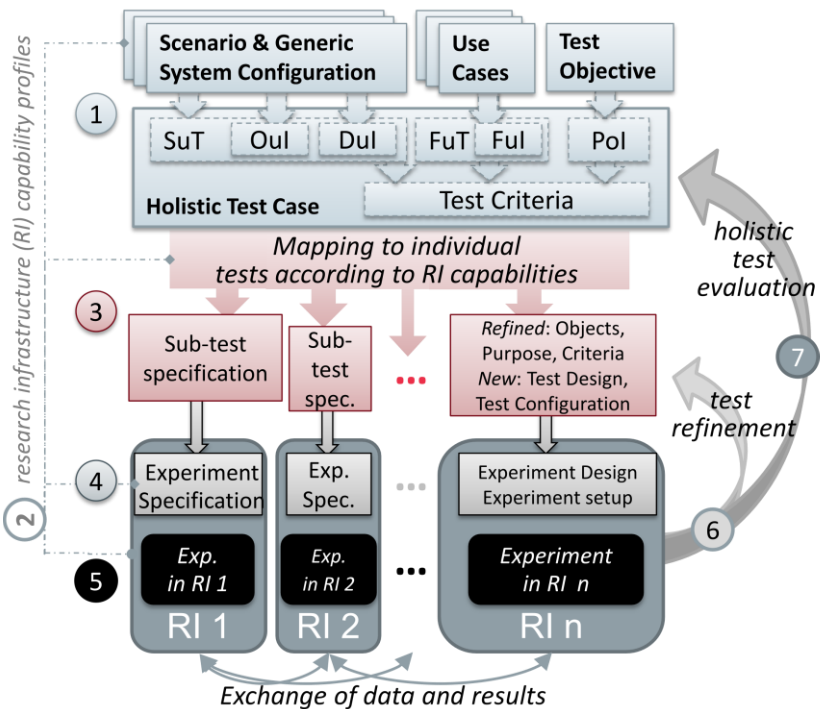

Figure 1: Overview of the ERIGrid validation approach for power systems [Bla16]

1.4.1 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. In a nutshell, the approach is divided into multiple layers, starting with the definition of test cases, which are then broken down into more detailed experiment specifications and in the end mapped to pilot or testing infrastructure where the tests are executed. More information about the ERIGrid approach can be found in D7.1 [FLED71] and [Bla16].

1.4.2 ERIGrid Validation Approach Applied to FLEXGRID

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

1. **Scenario Description:** In the first phase, different Validation Scenarios (VS) descriptions were collected that may be used to validate different aspects that are of interest for the three validation strands. To determine these validation scenarios, the FLEXGRID UCS from WP2 work 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 was made of what can be tested using this architecture.
3. **Mapping:** The mapping step is used to map the identified VS from Step 1 with the RI profiles from Step 2.
4. **Experiment Specification:** Following the mapping, detailed experiments have been specified based on each VS.
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.

Steps 1, 2, and 3 were covered in D7.1 [FLED71]. This deliverable focuses on the final steps from Step 4 to Step 7 for the lab validation strand. Experiments are specified, carried out and analysed. The experiments for the pilot validation strands are covered in D7.3.

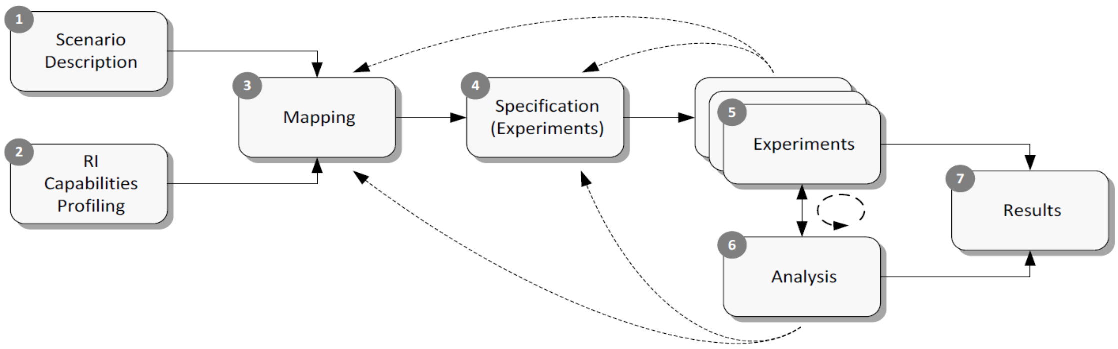

Figure 2: Validation methodology for the validation strands in FLEXGRID.

2 Evaluating Advanced Market Clearing Algorithms and x-DLFM Architectures

This validation strand covers the validation of the DLFM architectures developed in the FLEXGRID project using a Scalability and Replicability Analysis (SRA).

2.1 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 distribution-level 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].

The goal with this validation strand is to validate the DLFM architectures using an SRA approach. Due to current regulatory limitations and the complexity and novelty of some of these DLFM architectures, they will be tested using realistic simulations at the AIT SmartEST laboratory at TRL 4. The tests of the DLFM architectures have the following main goals:

- To reimplement the DLFM optimization algorithms using a Optimal Power Flow (OPF) Class C instead of the LinDistFlow solution from D5.3 [FLED53]
- Replicability study of the results from D5.3 [FLED53]
- Scalability study of the DLFM architectures using a realistic distribution system from bnNETZE

The scalability analysis will be done using both the original implementation of the DLFM algorithms from D5.3 [FLED53] and the re-implementation using an OPC Class C instead of the LinDistFlow algorithm. The following section contains an overview of the different DLFM architectures. This is followed by the experiments in Section 3 and Section 4.

In the experiments in Section 3 and Section 4, the results from the simulations are flexibility costs for the TSO as well as for the DSO.

For all results throughout the whole document, the costs are normalized for better comparison purposes.

2.2 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. More information about the DLFM architectures can be found in D5.3 [FleD53].

2.2.1 Benchmark – No Distribution Level Flexibility Market (No-DLFM)

As benchmark market architecture, no-DLFM system model is assumed, which is depicted in Figure 3. In the vertical axis, the temporal sequence of markets is illustrated. For example, in today's EU regulatory framework, where there exist no distribution-level markets, 3 main markets are assumed, namely: (i) Day-ahead energy market, (ii) day-ahead reserve market, and (iii) near-real-time balancing market.

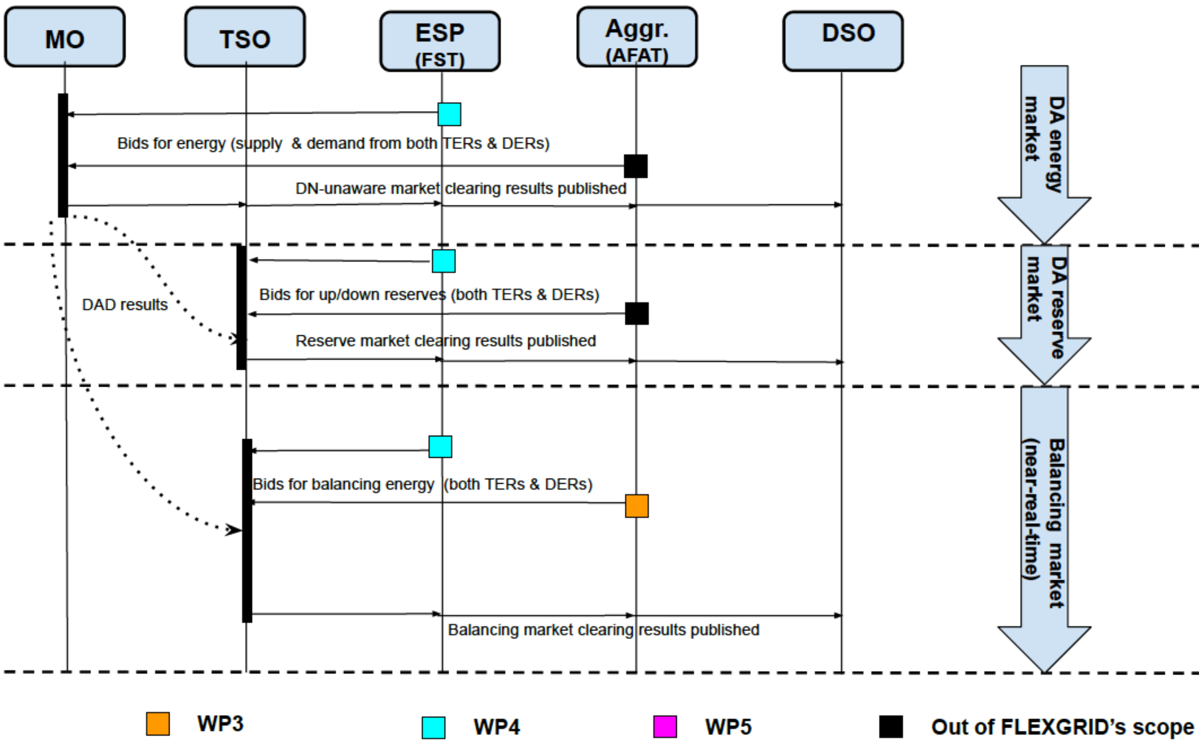

Figure 3: No-DLFM architecture representing the today's EU regulatory framework

2.2.2 Reactive Distribution Level Flexibility Market (R-DLFM)

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 overview of the R-DLFM is seen in Figure 4.

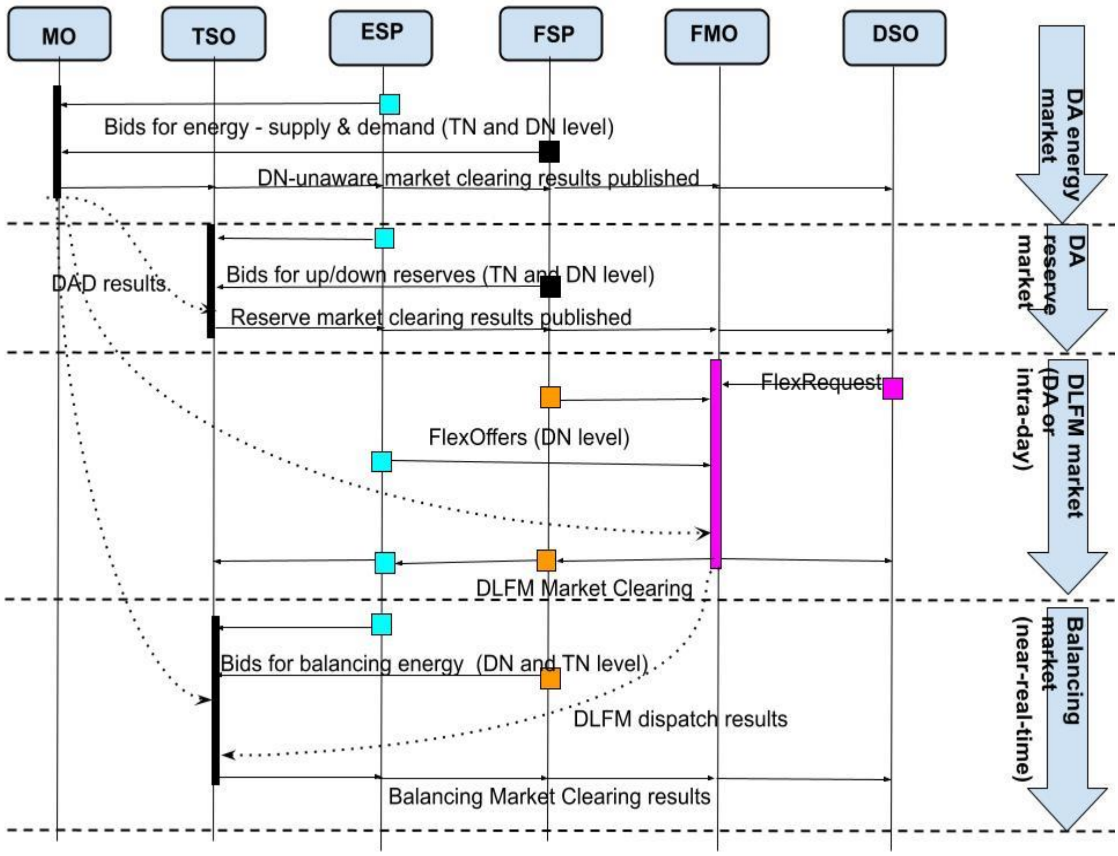

Figure 4: Reactive Distribution Level Flexibility Market (R-DLFM)

2.2.3 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 5.

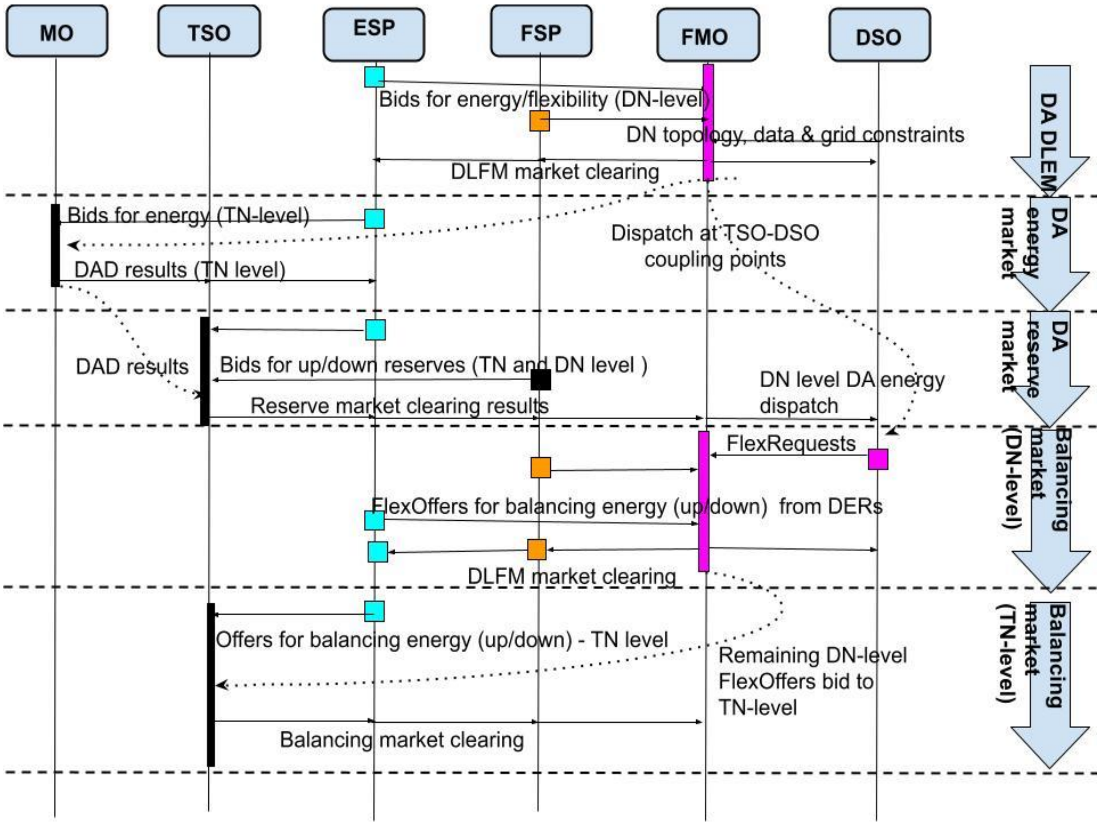

Figure 5: Proactive Distribution Level Flexibility Market (P-DLFM)

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.

2.2.4 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 6 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).

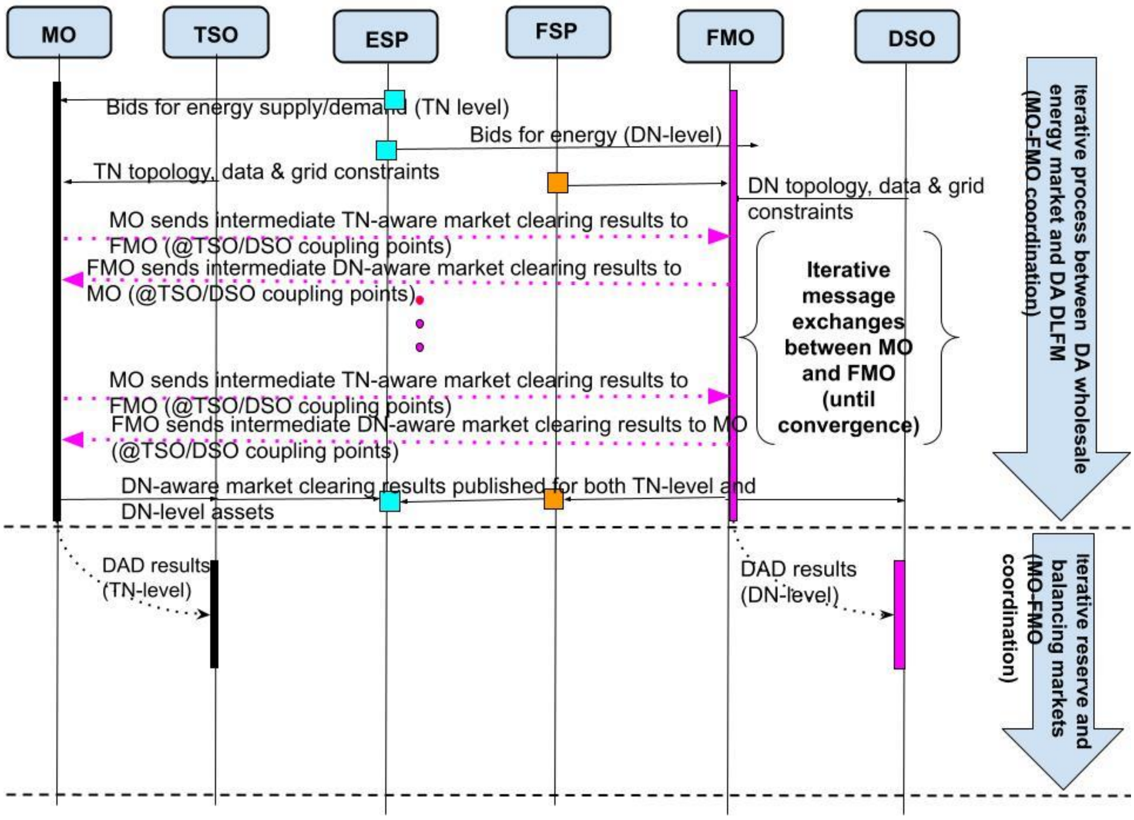

Figure 6: Market based smart grid architecture with optimal social welfare

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.

3 Scalability And Replicability Analysis of DLFM using Optimal Power Flow "Class C"

3.1 Simulation Environment

The first Scalability and Replicability Analysis (SRA) is performed using Optimal Power Flow "Class C" for the three-market approaches developed and presented in D5.3 [FleD53], namely Interactive Distribution-Level Flexibility Market (I-DLFM), Proactive Distribution-Level Flexibility Market (P-DLFM) and Reactive Distribution-Level Flexibility Market (R-DLFM).

3.1.1 Literature Review

Optimal Power Flow (OPF) is one of the most basic functions of ADMS. Various OPF algorithms can be found in the literature. The authors in [Dom68] describe an OPF algorithm for controlling active, reactive power, and transformer taps. The aim is to minimize system costs and losses. This method is based on the Newton-Raphson load flow. The achievable power current is resolved, and the optimum is close to the load current solution. Therefore, the Jacobian information is used to linearly calculate the optimum. In [Sas69], a non-linear programming technique is used to provide a solution to the OPF problem, with the aim of economical transfer and minimization of generation costs. As before, the load flow is performed to determine a workable solution. The Fletcher-Powell method is used to minimize the objective function. A general economic shipping problem was implemented in [Ela69]. This approach is similar to that in [Dom68], [Sas69]. An OPF method for planning energy systems is provided in [Pes72]. It used the generalized reduced gradient technique to find the optimum. The OPF method based on the Hessian matrix is illustrated in [Sas73]. It combines non-linear programming Newton-based methods and uses the Hessian matrix load current to minimize the quadratic goal. The authors in [Bal78] have described an OPF method that uses a reduced Hessian matrix with systematic restriction treatment. It provides an accurate solution, good convergence, and a description of the acceleration factor. An OPF problem with stationary security is presented in [Als74]. It is an extension of [Dom68] that contains precise restrictions for unforeseen errors. In [Hap74], a solution for the optimal dispatch problem was implemented with the help of the Jacobian matrix. It offers a quick convergence that can be used in the online exam. An OPF algorithm based on a reduced gradient method is proposed in [Muk74]. It is used to minimize generator load and optimize voltage levels. Load flow equations are shown as equality constraints. In [Lip81], modified OPF based on recursive quadratic programming (MRQP) is implemented. MRQP is based on [Ela69]. In [Ras74], an OPF algorithm is specified, which uses the Newton method with Hessian instead of the Jacobian matrix and Lagrange multipliers. It offers good convergence compared to its predecessors. An algorithm for solving a large OPF problem is presented in [Bur82]. It breaks down the original main problem into a number of sub-problems that are linearly bounded with the extended Lagrange operator.

In 1991, Glavitsch et al. classified various OPF techniques into two categories [Gla91]. "Class A" describes a set of algorithms that use ordinary load flow to obtain an interim solution, and this solution is close to optimal load flow solutions under normal conditions. The optimization is performed iteratively using the Jacobian matrix and several other sensitivity relationships.

A new load current is executed with each iteration. The optimal solution in this class depends heavily on the accuracy of the load flow solution. With a load flow solution, a set of voltages and phase angles, the Jacobian matrix, and a set of incremental power flow equations are available or can be expanded. If a load flow solution exists, it already fulfils all the boundary conditions. The optimization problem is solved separately by taking into account the sensitivity relationship from the past in order to obtain an optimal one. An implementation of a class A algorithm is given in [Dom68]. Another example of such an implementation is given in parts one and two in [Sto78], respectively, using linear programming.

"Class B" refers to the class of algorithms that depend on exactly optimal conditions and therefore use load flow equations as equality constraints. The optimal solution depends on a detailed formulation of the OPF problem with the entire search area. This does not require a load flow solution. However, these types of problems are non-convex in nature. Hence, convex relaxation or non-convex solvers are needed to compute the optimum, which brings its own problems. It deals with the optimality conditions of the Lagrange function and consists of derivatives of constraints and objective functions. Since the Hessian matrix is sparse and remains constant, it further increases the simplicity of this method and the ease with which the optimum is achieved. Dealing with constraints is one of the greatest challenges for this class of algorithms. Limitations are treated in a heuristic procedure as punishment terms that have to be adjusted at every step and thus lead to a deterioration in performance.

The above two classes of algorithms have different advantages and disadvantages. Class A performance is directly related to the performance of load flow techniques such as Newton-Raphson, Gauss-Seidel, and the widely used method of fast decoupling. In [Tri12], it is shown that the above methods have convergence and robustness problems. This can lead to inaccurate charging current solutions. If the load flow does not lead to a so-called high-voltage or practical solution, class A algorithms fail. With class B algorithms, it is difficult to get a global operable solution because it requires convex relaxation or heuristic techniques, and the operable solution is difficult to achieve, taking all boundary conditions into account.

The authors in [Rao19] have presented a third class of algorithms, a "Class C". This class combines class A and class B. It uses a reliable load flow wrapped around a heuristic to produce the optimal solution. The load flow provides an accurate, workable voltage and phase angle solution at each step, and the heuristic uses this as equality constraints as described in class B. Class C algorithms offer several advantages. With the Holomorphic Embedding load flow method (HELM), one gets a usable voltage and phase angle solution with every iteration. HELM always finds a solution, if available, regardless of the initial conditions, while the Newton-Raphson Load flow method leads to a non-convergent solution for very low or high load conditions [Tri12]. Since HELM is used in the class C process, the results are high voltage and usable. A global OPF solution can be obtained with a non-convex solver.

OPF "Class C" is defined as an optimization problem as follows:

$$
\begin{aligned}
\underset{u}{\text{minimize}} \quad & F(x,u) \\
\text{subject to} \quad H(x,u) & = 0, \\
G(x,u) & \leq 0
\end{aligned}
$$

where $F(x,u)$ is the objective function. $H(x,u)$ and $G(x,u)$ are the equality and inequality constraints, respectively.

x, u are the status and input variables. In a low-voltage distribution network that only contains load buses, the input variables in the context of the loads are active and reactive power feed-in or consumption at loads, while the state variables are voltages, phase angles and reactive powers on all buses.

Active power limitation profiles must be generated on all controllable buses in the network.

3.1.2 Inequality Constraints

Set of inequality constraints $G(x,u)$, are described as follows with limits on active power of controllable devices, $c \in C$, set of controllable devices and $t \in T$, time horizon,

Limits on active power (kW) of a (generator) PV node:	$P_{Low_i} \leq P_{PV_i} \leq P_{High_i}$
Limits on voltage (V (pu.)) of a PV or PQ node:	$\lvert V_{Low_i}\rvert \leq \lvert V_i\rvert \leq \lvert V_{High_i}\rvert$
Limits on tap positions of a transformer:	$t_{Low_i} \leq t_i \leq t_{High_i}$
Limits on phase shift angles of a transformer:	$\theta_{Low_i} \leq \theta_i \leq \theta_{High_i}$
Limits on shunt capacitances or reactances:	$s_{Low_i} \leq s_i \leq s_{High_i}$
Limits on reactive power (kVAr) generation of a PV node:	$Q_{Low_i} \leq Q_{PV_i} \leq Q_{High_i}$
Upper limits on active power flow in transmission lines or transformers:	$P_{i,j} \leq P_{High_{i,j}}$
Upper limits on MVA flows in lines or transformers:	$P_{i,j}^2 + Q_{i,j}^2 \leq S_{High_{i,j}}^2$
Upper limits on current magnitudes in lines or transformers:	$\lvert I_{i,j}\rvert \leq \lvert I_{High_{i,j}}\rvert$
Limits on voltage angles between nodes:	$\Theta_{Low_i} \leq \Theta_i - \Theta_j \leq \Theta_{High_i}$

P, Q, V, and θ are active power, reactive power, voltage, and phase shift angle. s is the shunt reactances or capacitances. Θ is the voltage phase angle.

3.1.3 Equality Constraints

The results of the load flow are used as constraints $H(x,u)$ as described in class C of OPF algorithms. Load flow methods based on numerical techniques are able to solve a system of non-linear equations [Tri12]. The convergence of such methods cannot be ensured since the operational solution depends directly on the assumed initial seed (starting point or initial condition). If the system has multiple solutions, it is difficult to determine if the converged solution is operational. Therefore, to overcome the limitations of iterative numerical solutions, HELM is used in this research work. The distribution grid is modelled on the basis of the methodology developed in [Baz18].

Power flow equations, for example, the load bus equation described in the equation below, are inherently non-analytical. Holomorphic principles can be applied to such equations by including a complex variable so that the resulting problem is analytical in nature.

$$\sum_{k\in\Omega} Y_{ik}V_k = \frac{S_i^*}{V_i^*},\ \ i \in \Omega_{PQ}$$

The voltage of the slack bus is assumed to be V_0 = 1.0 pu. and Bus 00 is always set to be the slack bus.

Holomorphic embedding can be done in various methods. The equation above represents the simplest form. Bus voltages are the functions of the demand scalable complex variable α.

$$\sum_{k\in\Omega} Y_{ik}V_k(\alpha) = \frac{\alpha S_i^*}{V_i^*(\alpha^*)},\ \ i \in \Omega_{PQ}$$

The research work in [Tri12] suggests that the operable voltage solution can be obtained by analytic continuum at $\alpha = 1$ using the unique solution which exists when $\alpha = 0$

$$\sum_{k\in\Omega} Y_{ik}V_k(\alpha) = \frac{\alpha S_i^*}{\overline{V}_i(\alpha^*)},\ \ i \in \Omega_{PQ}$$
$$\sum_{k\in\Omega} Y_{ik}^*\overline{V}_k(\alpha) = \frac{\alpha S_i}{V_i(\alpha)},\ \ i \in \Omega_{PQ}$$

The equations above represent a set of polynomial equations, and by using the Grobner bases, V_i and $\overline{V}_i$ are holomorphic except for finite singularities. According to [Tri12], if the equations above hold good, then they can be reduced to an equation using the reflective property.

$$\overline{V}_i(\alpha) = (V_i(\alpha^*))^*,\ \ i \in \Omega$$

Since voltages for $\alpha = 0$ as discussed above, it can be extended to the power series described below.

$$V_i(\alpha) = \sum_{n=0}^{\infty} V_i[n]\alpha^n,\ \ i \in \Omega$$
$$\frac{1}{V_i(\alpha)} = W_i(\alpha) = \sum_{n=0}^{\infty} W_i[n]\alpha^n,\ \ i \in \Omega$$

Power series coefficients can be calculated to the desired degree,

$$\sum_{k\in\Omega} Y_{ik}^* \sum_{n=0}^{\text{inf}} V_k\,[n](\alpha^n) = \alpha S_i^* W_i^*[n]\alpha^n$$

The following steps are involved in calculating voltages. For $\alpha = 0$, the equation above is solved to obtain a linear equation where the left-hand side of the equation represents the slack bus at which $V_0[\alpha] = 1$.

$$\sum_{k\in\Omega} Y_{ik} V_k[0] = 0, \;\; i \in \Omega_{PQ}$$

The reduced Y bus matrix is assumed to be non-singular based on the non-singularity assumption.

$$W_i[0] = \frac{1}{V_i[0]}$$

The remaining power series coefficients can be obtained to the desired n^{th} degree by equating the coefficients.

$$\sum_{k\in\Omega} Y_{ik} V_k[0] = S_i^* W_i^*[n-1], \;\; i \in \Omega_{PQ} \;\; n \geq 1$$

$W_i[n-1]$ are calculated using the lower order coefficients.

$$W_i[n-1] = -\frac{\sum_{m=0}^{n-2} V_i[n-m-1]\, W_i[m]}{V_i[0]}$$

Pade approximations, which are a special type of rational approximation, are used for the analytical continuum to determine the voltages $\alpha = 1$.

3.2 Replication Study of IEEE One-Area Reliability Test System and 15-Bus Radial Distribution Network

3.2.1 Experiment Description

The goal of this experiment is to replicate the study, which was done for D5.3 [FLED53] using the OPF “Class C” described above. Here, the main goal is to achieve a baseline for the following SRA using the distribution system from bnNETZE.

3.2.2 Validation Environment and Setup

The three market structures are applied to the IEEE one-area reliability test system, shown in Figure 7 and a 15-node radial distribution network, shown in Figure 8. The objectives and constraints are based on work conducted in [Sek22] and D5.3 [FLED53].

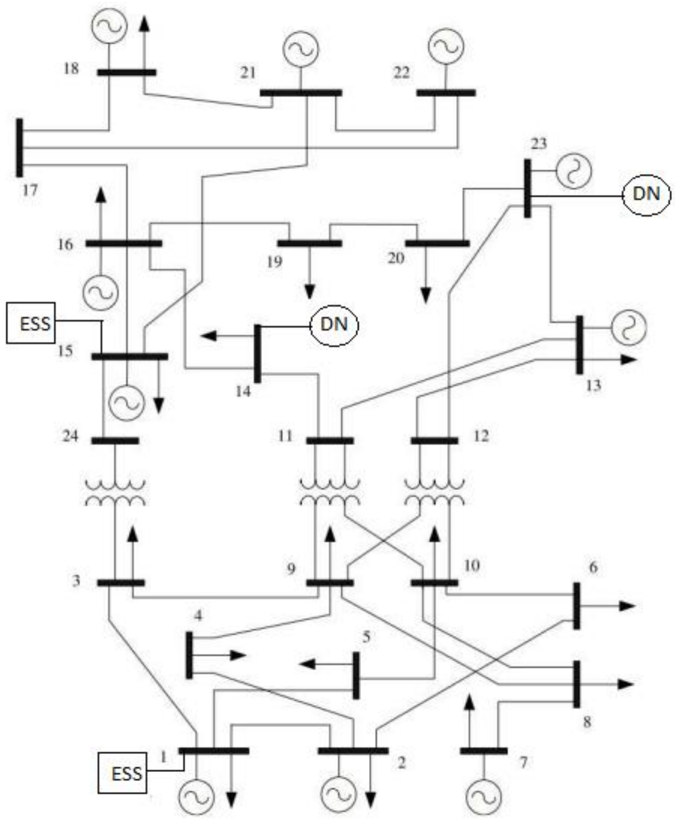

Figure 7: The IEEE One-Area Reliability Test System

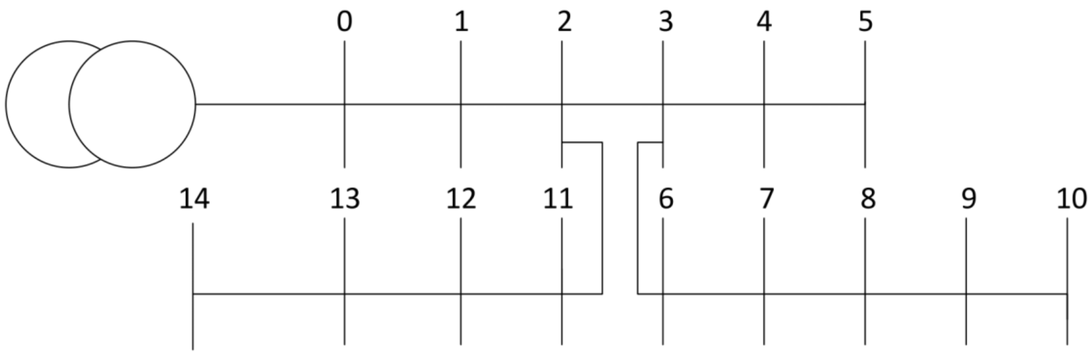

Figure 8: A 15-Node Radial Distribution Network

3.2.3 Performed Tests and Results

Figure 9 shows the TSO (or else TN-level) costs for various RES penetration scenarios. It can be observed that R-DLFM approach produces least costs for the TSO. This is due to not considering grid constraints in the optimization problem. R-DLFM is not grid aware, compared to I-DLFM and P-DLFM. With the increase in RES, the overall costs for TSO reduce as RES generation and conventional DGs cancel out the cost of loads in both transmission and Distribution levels. When looking at the total cost (for both TSO and DSO), it is actually the least for the I-DLFM, but in Figure 9 only the TSO costs are shown. Thus, as the I-DLFM considers both grid and flexibility constraints, the costs are higher for the TSO when compared to other approaches. Additionally, for R-DLFM, flexibilities at the DSO is activated to lower the costs at the TSO level.

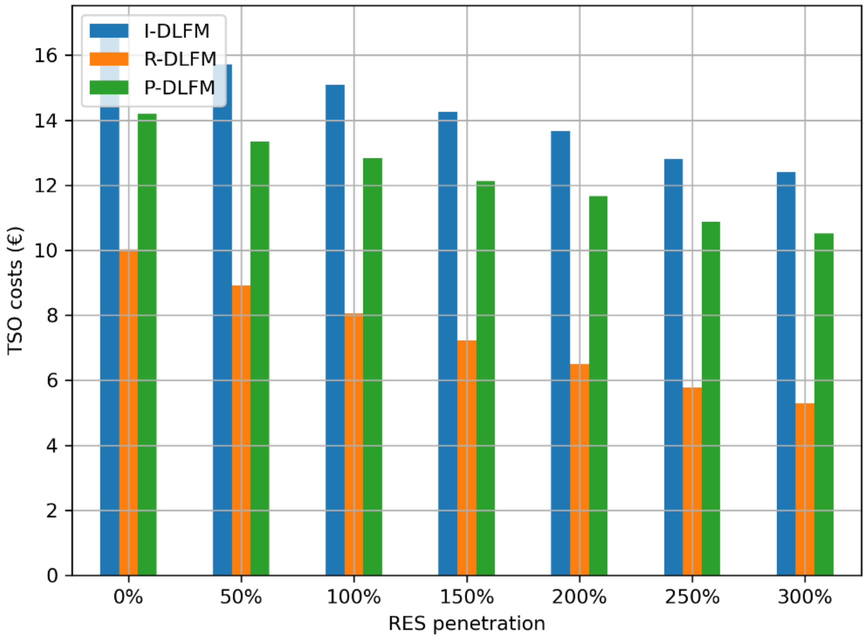

Figure 9: Comparison of x-DLFM architectures in terms of TN-level energy cost for several RES penetration scenarios, for the test grid.

Figure 10 represents the flexibility costs for various flexibility scenarios. It can be observed that the No-DLFM approach performs the worst, leading to high flexibility costs. However, the R-DLFM with high flexibility scenario leads to least flexibility costs. This is due to the fact that the grid constraints are not considered at the DSO level for the No-DLFM and therefore, the RES and flexibilities like ESS are not curtailed, leading to lower costs for R-DLFM.

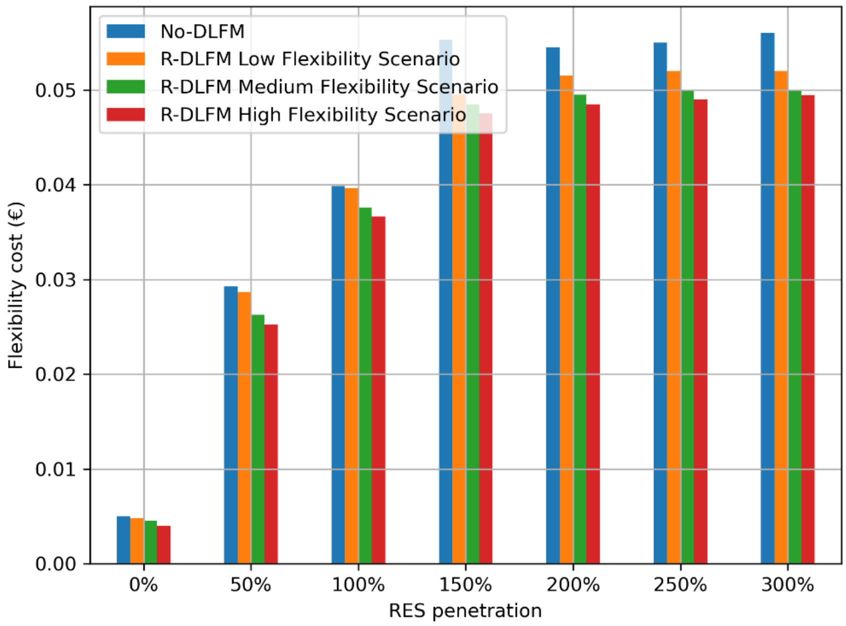

Figure 10: DSO flexibility Cost in No-DLFM and R-DLFM for the test grid.

3.3 SRA Study using bnNETZE's Distribution Grid

3.3.1 Experiment Description

In this section, a real grid from bnNETZE control area was used for scalability and replicability analysis.

3.3.2 Validation Environment and Setup

The main electricity grid of bnNETZE lies within the city limits of Freiburg. This is the core grid. It consists of five 110/20 kV substations working as coupling points to the superior grid. All these substations are interconnected by a 110 kV ring. The energy is transported locally on a MV grid operated with 20 kV. Finally, the LV grid is responsible for transporting the energy to the customers.

Several smaller cities and villages in the direct neighborhood are supplied also. Some of them are directly connected to the core grid in the city via MV-links. Thus, here is a direct coupling and in consequence their supply is metered in the coupling points to the superior 110 kV grid together with the demand in the city. Further two smaller utilities are directly connected to this grid. Some villages and cities are too far away, so they have own coupling points to the superior grid.

In total the electrical grid covers an area of about 690 km² and has a length of almost 5,960 km. Around 202,000 meters are installed (as of December 2018). The topology of the distribution grid from bnNETZE is seen in Figure 11.

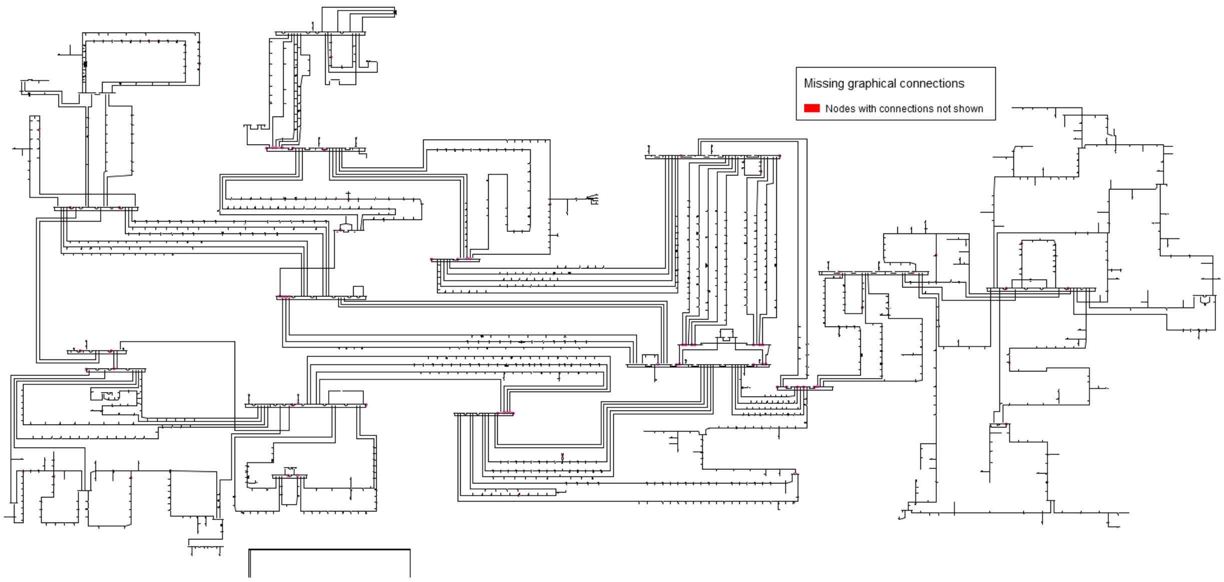

Figure 11: Topology of bnNETZE's real grid

To perform the SRA, a total of nine scenarios are defined:

1. Grid loading constraint scenarios – Three scenarios to check the behavior of the three markets for various grid loading scenarios. Meaning, the voltage and line loading of the grid is considered.
    a. Low loading
    b. Medium loading

c. High loading
2. Electric Energy Storage penetration scenarios – Varying degrees of penetration of EES.
   a. Low flexibility penetration
   b. Medium flexibility penetration
   c. High flexibility penetration
3. Renewable energy and conventional DG penetration scenarios – Varying degrees of RES and DGs for SRA analysis.
   a. Low-RES and conventional DG penetration
   b. Medium RES and conventional DG penetration
   c. High-RES and conventional DG penetration

3.3.3 Performed Tests and Results

3.3.3.1 Grid loading constraints scenarios

Using loads, RES and conventional DG, the transmission and distribution grids are loaded up to 30%, 60% and 90%, statistically, to generate the behavior for the three markets. The results can be observed in Figure 12. As expected, the grid state has no effect on the R-DLFM market as the grid constraints are not considered. However, the grid state should be considered for safe operation of the transmission and distribution grid. This is one of the limitations of the R-DLFM method. Meanwhile, the TSO costs are higher for I-DLFM and P-DLFM due to unavailability of grid capacity for load flow as the grid is heavily loaded.

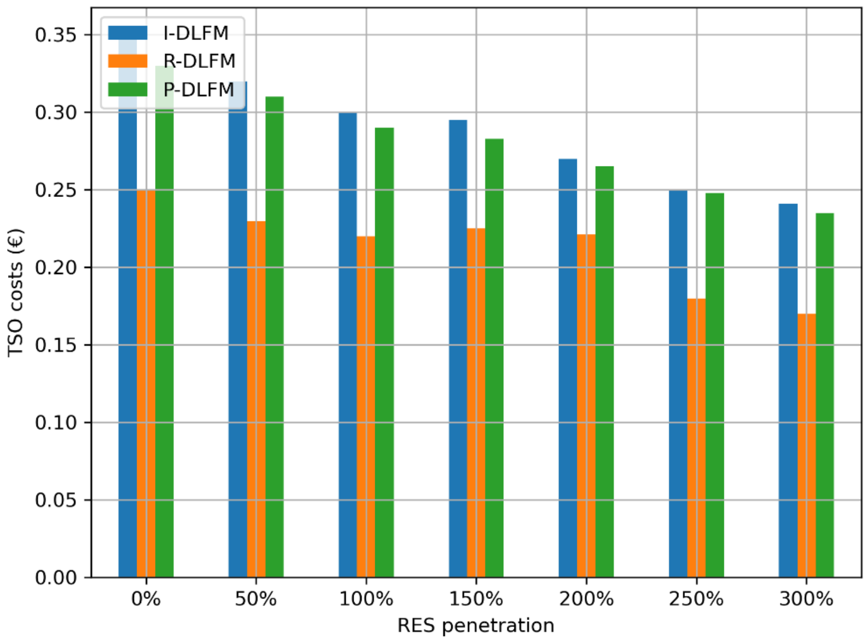

Figure 12: Comparison of x-DLFM architectures in terms of TN-level energy cost for several RES penetration scenarios, for high grid loading scenario.

Figure 13 shows the behaviour of the No-DLFM and R-DLFM for the DSO flexibility costs. Similar behaviour as Figure 10 is observed. Due to very limited available grid capacity, the utilization of flexibility is limited for medium and high loading scenarios. As No-DLFM scenario does not have any active control actions, it is evident that the total costs are higher than all other approaches. The coordinated control of TSO and DSO assets lead to a more optimal solution for the entire system.

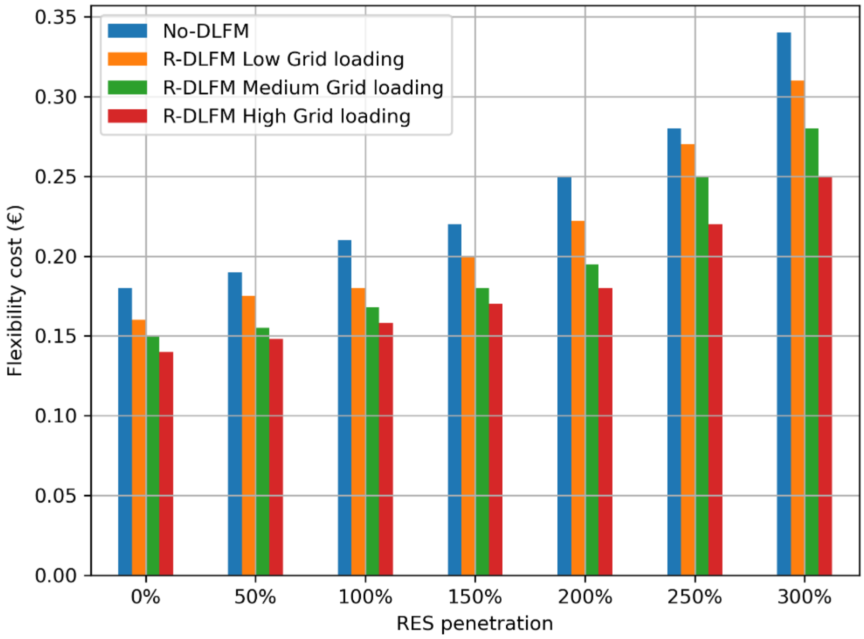

Figure 13: Flexibility Cost in No-DLFM and R-DLFM

3.3.3.2 Electric energy storage system scenarios

EES penetration is increased from 30%, 60% and 90% (100% penetration represents EES connected at all of the 1269 loads in the grid) to generate the behaviours of the three DLFM architectures. Figure 14 shows the TSO costs for high EES penetration. It can be observed that the TSO costs are lower due to the presence of large number of EES systems in the DSO level. Most of the RES production can be stored in the EES system, reducing the overall TSO costs. Again, since only the TSO costs are shown, the costs for the I-DLFM are the highest.

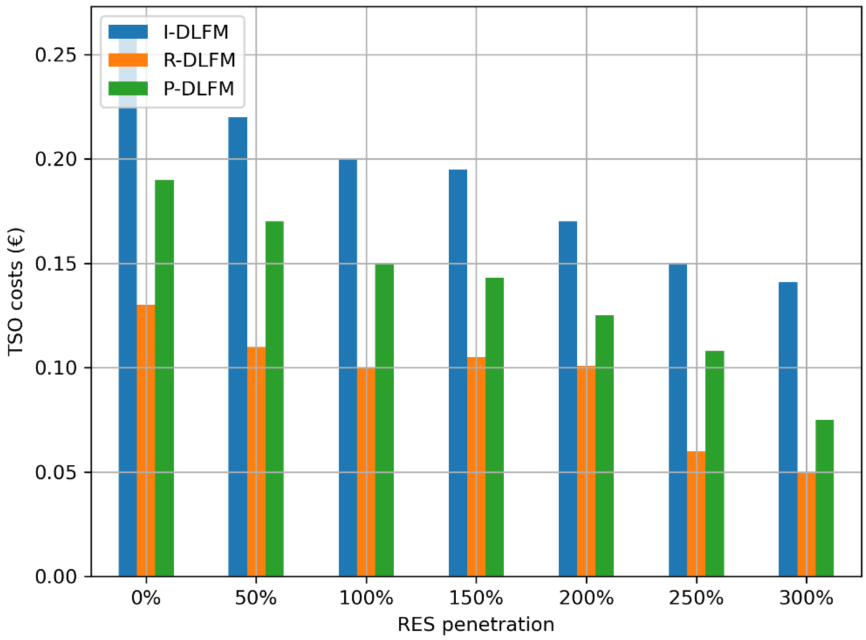

Figure 14: Comparison of x-DLFM architectures in terms of TN-level energy cost for several RES penetration scenarios, for high EES penetration scenario.

Figure 15 represents the R-DLFM for various EES penetration scenarios. It is evident that the DSO flexibility costs are significantly lower compared to Figure 13. With increase in flexibility at the DSO level, the FMO can activate flexibility units leading to more renewable energy utilization and lowers the generation cost of the DSO.

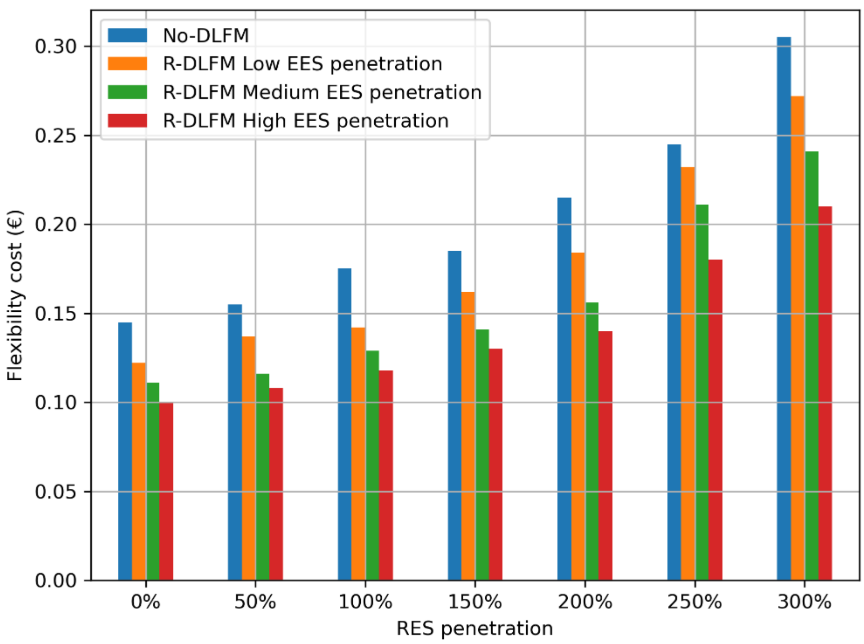

Figure 15: DSO flexibility cost in No-DLFM and R-DLFM for bnNETZE's distribution grid.

3.3.3.3 Renewable energy and conventional DG penetration scenarios

With the increase in renewable energy generation in distribution grids, it is essential to analyze the three market architectures with varying degrees of RES and conventional DGs. In the following, simulations were done with 30%, 60%, and 90% of RES and conventional DG penetration. Figure 16 presents the resulting TSO costs for the three market structures. In this scenario, the TSO costs are not as low as Figure 13. This is due to not having enough flexibilities through connected EES systems (in this case 30% EES penetration was used) in the distribution grid. Figure 17 presents the R-DLFM based on various renewable energy and conventional DG penetration scenarios. Similarly, the performance is not as good as Figure 14 due to unavailability of large number of EES for maximizing the utilization of renewable generation (also here 30% of the 1269 possible EES systems were used).

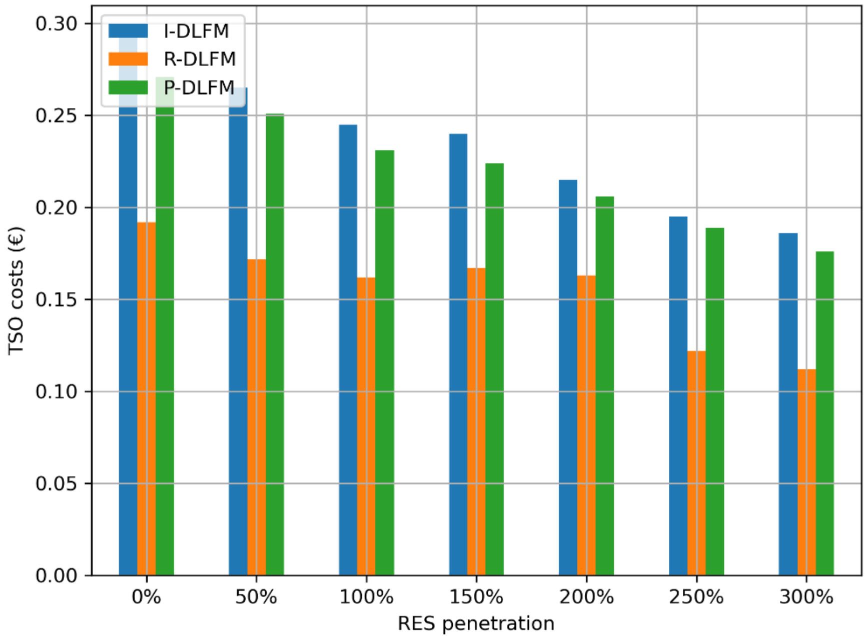

Figure 16: Comparison of x-DLFM architectures in terms of TN-level energy cost for several RES penetration scenarios, for high renewable energy sources and conventional DG penetration scenario.

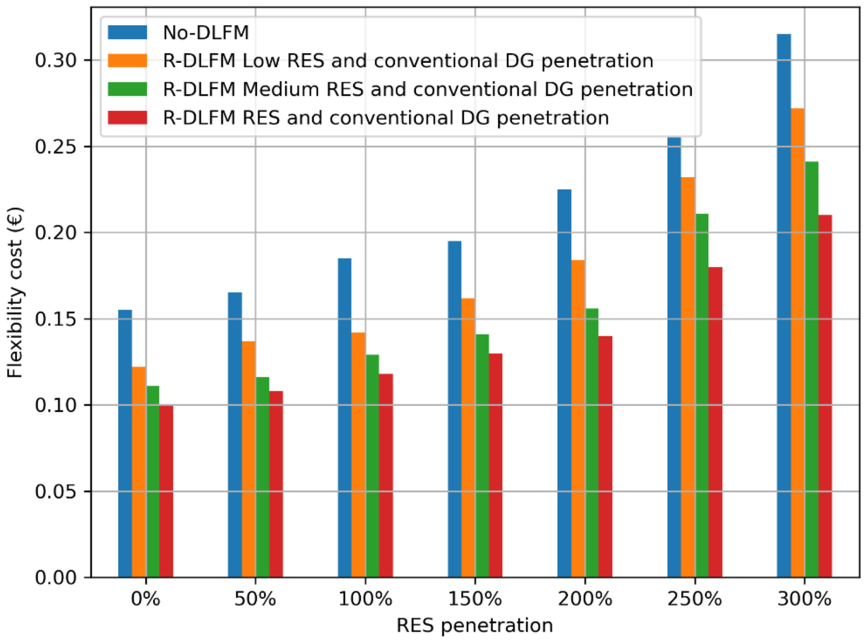

Figure 17: DSO flexibility cost in No-DLFM and R-DLFM for bnNETZE's distribution grid.

3.4 Evaluation of Results

The scalability and replicability analysis was performed on the three-market architecture approaches developed, namely Interactive Distribution-Level Flexibility Market (I-DLFM), Proactive Distribution-Level Flexibility Market (P-DLFM) and Reactive Distribution-Level Flexibility Market (R-DLFM). This was performed using an Optimal Power Flow "Class C" algorithm, in contrast to the convex relaxed mixed-integer linear programming OPF developed in D5.3 [FLED53]. Replicability analysis was first performed on the test grids shown in Figure 7 and Figure 8. These results are comparable to the work performed in [Sek22] and D5.3 [FLED53] as shown in Figure 9 and Figure 10. Next, a scalability and replicability study was performed on a real grid from Germany, from the control region of bnNETZE. Similar approach is applied at the test grid for three scenarios. Namely, (i) grid loading constraints, (ii) EES penetration scenario and (iii) conventional DG and RES penetration scenario. Various behaviours of the three market approaches are described. There is a need for increased cooperation between TSOs and DSOs to tackle the challenges due to climate change and the need for large integration of climate friendly RES generation and electro mobility at the DN-level in future power grids. Innovative market architecture approaches developed in the FLEXGRID project will help positively the grid and all stakeholders involved.

4 Scalability And Replicability Analysis of DLFM using LinDistFlow Coupled with PowerFactory

4.1 Simulation Environment

The Scalability and Replicability Analysis (SRA) is performed for the three x-DLFM architectures presented in Section 2.2. For this experiment the grid data from bnNETZE presented in Section 3.3.2 was used. The bnNETZE data is available as PowerFactory model. PowerFactory is a leading power system analysis software (commercial tool), which covers the full range of functionality from standard features to highly sophisticated and advanced applications [DIG22]. 24 hours with 15 minutes interval load and generation profiles are generated based on measured and estimated data using the feeder load scaling tool of PowerFactory. There was no direct coupling between the different market algorithms under investigation and the PowerFactory tool. The grid information and the load data were exported in form of excel files and conducted as the main input to the different tested market algorithms developed in D5.3 [FleD53].

4.2 SRA Study of DLFM using LinDistFlow and PowerFactory

4.2.1 Experiment Description

The three market structures are tested using real grid data from bnNETZE, shown in Figure 11. The objectives and constraints are based on work conducted in [Sek22] and D5.3 [FleD53] (see chapter 5 of D5.3 for more details about the mathematical modelling).

To perform the SRA, three different flexibility scenarios were developed with different RES penetrations levels:

1. Low, medium and high RES and DG penetration
2. Low, medium and high load flexibility penetration
3. Low, medium and high EES penetration

A base case scenario has been created using a feeder load scaling tool of DigSILENT PowerFactory. The load and generation data are generated based on real measured data. Loads and PV scenarios were defined through scaling up their profiles.

Similar results are obtained by comparing the results from testing the Matlab algorithms and the PowerFactory DigSILENT simulation tool with Python interface.

4.2.2 Validation Environment and Setup

The three x-DLFM architectures are applied to the IEEE 30 bus system, shown in Figure 18 and the medium voltage grid of bnNETZE (20 kV level), shown in Figure 11 . The objectives and constraints are based on work conducted in [Sek22] and D5.3 [FLED53].

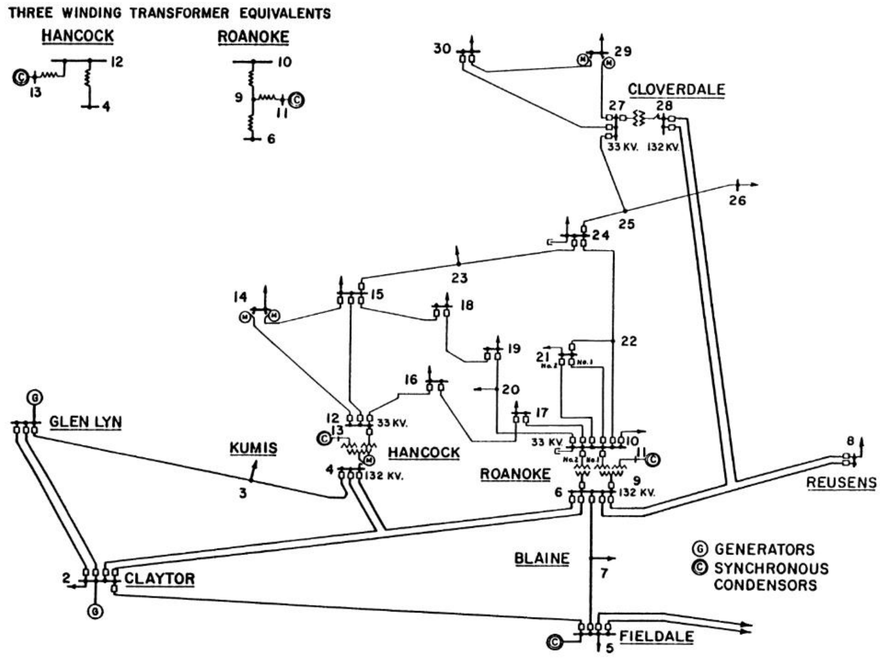

Figure 18: The IEEE 30-bus system

4.2.3 Performed Tests and Results

4.2.3.1 Renewable energy and conventional DG penetration scenarios

Different scenarios of PV and DG penetration on high and medium voltage level were considered. As shown in Figure 19, the TSO costs are higher for I-DLFM and P-DLFM as the grid is heavily loaded. Especially, with 150 % RES penetration and above, it is seen that the P-DLFM costs becomes higher than the I-DLFM. This makes sense since for the P-DLFM the available RES are used on the DSO level first which increases the costs for the remaining flexibility on the TSO level. If both the costs for the TSO and the DSO would be considered, the I-DLFM would be the winner.

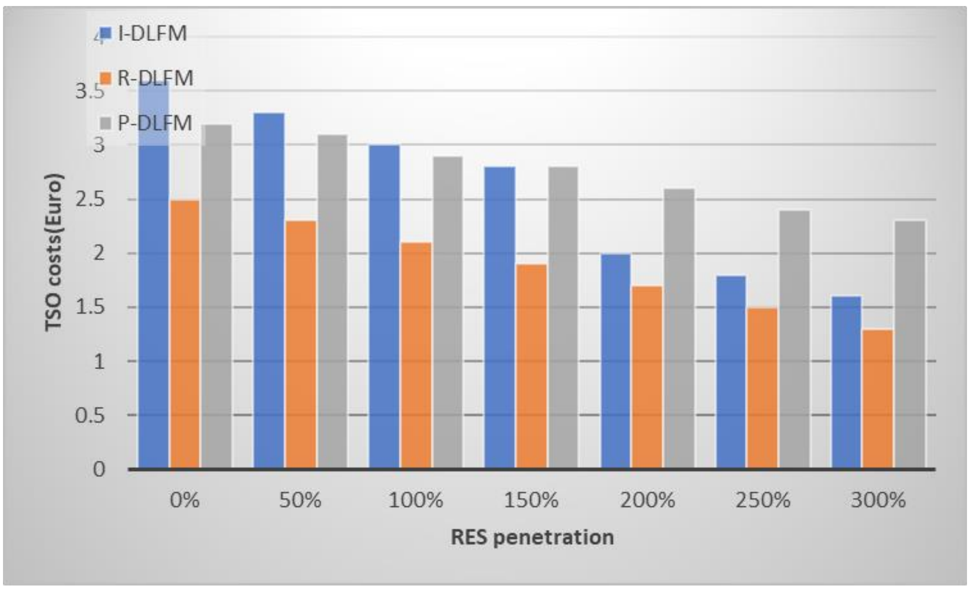

Figure 19: Comparison of x-DLFM architectures in terms of TN-level energy cost for several RES and DG penetration scenarios.

4.2.3.2 *Different flexibility penetrations*

Different load flexibility penetrations were considered from low to high level. Figure 20 shows that, the No-DLFM is the worst case as it has no flexibility capacity in the grid. The R-DLFM with high grid flexibility scenario leads to the minimum flexibility costs. Increasing the flexibility at the DSO level may lead to increase the utilization of more RES and lowering the TSO generation costs.

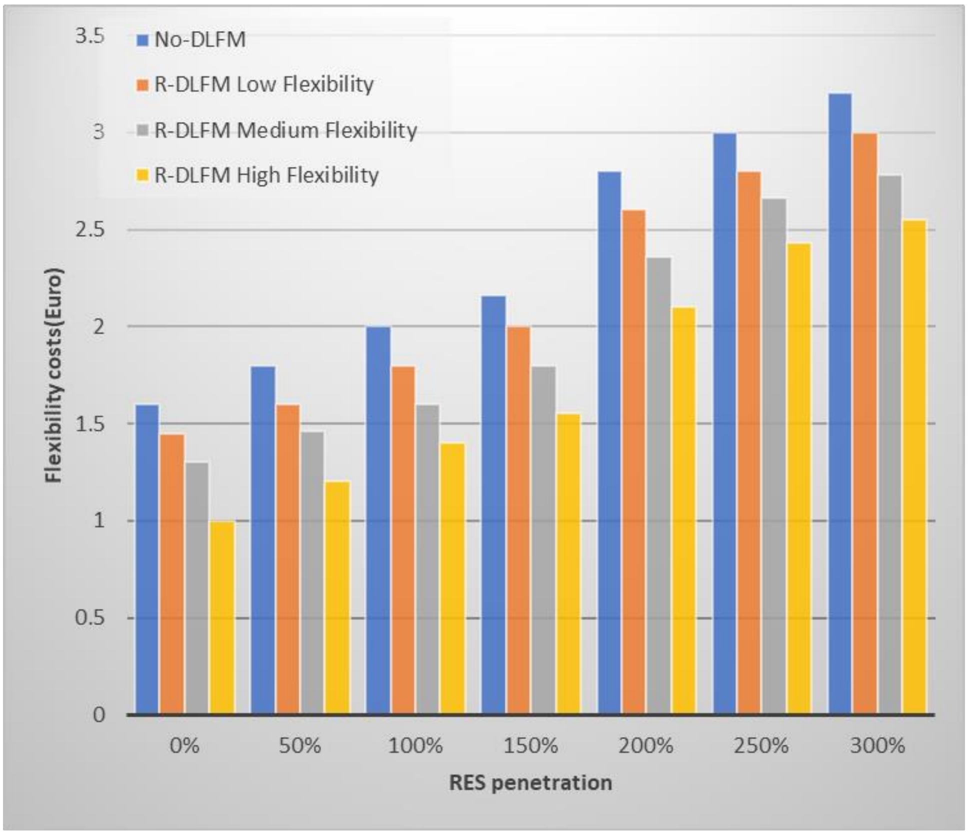

Figure 20: DSO flexibility cost in No-DLFM and R-DLFM.

4.2.3.3 *Electric energy storage system penetration scenarios*

The EES penetration was varied and increased to analyze the behavior of the three x-DLFM architectures. Figure 21 shows the results for the scenario with a high EES penetration. It shows that costs of TSO flexibility are lower due to the presence of big number of EES where PVs can store their production. It shows that the TSO flexibility costs (in terms of TN-level) with higher RES penetrations and the existence of EES is lower for the P-DLFM and higher for the I-DLFM.

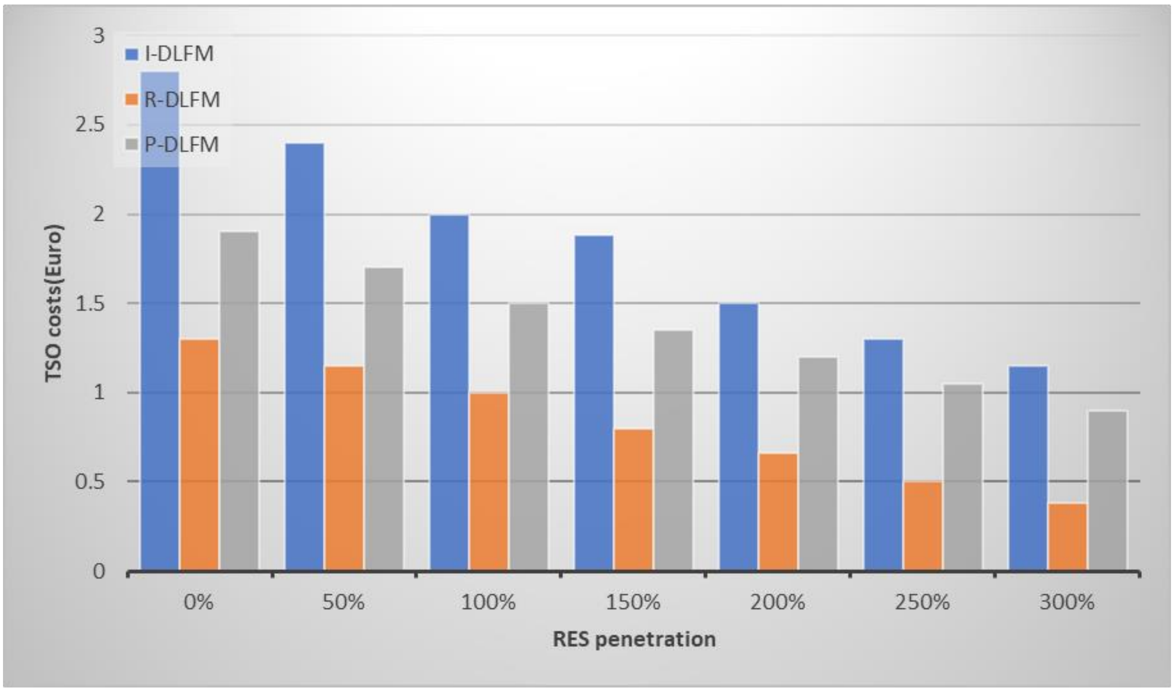

Figure 21: Comparison of x-DLFM architectures in terms of TN-level energy cost for several RES penetration scenarios, for high EES penetration scenario.

4.3 Evaluation of Results

The scalability and replicability analysis took place for the three x-DLFM architecture approaches developed, namely Interactive Distribution-Level Flexibility Market (I-DLFM), Proactive Distribution-Level Flexibility Market (P-DLFM) and Reactive Distribution-Level Flexibility Market (R-DLFM) architectures. This was performed by using the convex relaxed mixed-integer linear programming OPF developed in D5.3 [FLED53]. Replicability analysis was performed on the IEEE 30-bus system and a real grid from Germany, bnNETZE (20 kV) grid shown in Figure 11. The same approach was applied for three different flexibility scenarios developed with different RES penetrations levels:

1. Low, medium and high RES and DG penetration
2. Low, medium and high flexibility penetration
3. Low, medium and high EES penetration

The behaviour of the three x-DLFM market approaches is tested and described for the different described scenarios mentioned before. There is a need for increased cooperation between TSOs and DSOs to tackle the grid technical challenges on the DSO side due to the integration of large RES generation and electro mobility in future power grids and the expansion of their share in flexibility market.

In general, the no-DLFM scenarios do not have any active control actions, which is why the total costs for scenarios with no-DLFM are higher than all other approaches. The scenarios of different load flexibility levels show that the R-DLFM with high grid flexibility scenario leads to the minimum flexibility costs, while increasing the flexibility at the DSO level may lead to an increase in the utilization of more RES and lowering the TSO generation costs.

For different RES scenarios from low to high penetrations, the TSO flexibility costs decrease with the increase of the RES and EES penetrations, which shows that the costs of R-DLFM are the lowest. Thus, adding more EES at the DSO level helps to lower the costs on the TN level.

DSO participation in flexibility markets has a lot of challenges and barriers. DSO observation areas should be prioritized according to the available free capacity of the grid to ensure safe, secure, and reliable network operation. DSOs need to be sure that the participation of RES unit and or flexible load in the flexibility market will not lead to any local problems (grid congestion and voltage violations). Otherwise, flexibility sources located in geographical areas which are operated at the grid limits or supposed to have any operational limits violations, might need to be excluded from the flexibility market. More enhanced TSO-DSO cooperation methods, like the I-DLFM, which coordinate the access on these flexibility sources at both TSO and DSO level can ensure secure grid operations and thus also allow all RES to participate in the flexibility market.

5 Conclusions

Scalability and replicability analysis were performed for various innovative market structures developed in the project. Two main approaches were adopted to fortify scalability and replicability of various methods, tools for test grid and real grid of bnNETZE. The two approaches were:

1. Scalability And Replicability Analysis of DLFM using Optimal Power Flow "Class C"
2. Scalability And Replicability Analysis of DLFM using LinDistFlow Coupled with PowerFactory

The original models were developed using linear optimization models and linear load flow. However, the power flows are non-linear and non-convex in nature. In order to achieve more realistic results, the capture the power flow mechanism's non-linearity, OPF type C is used. OPF type C uses a non-linear, non-convex solver to calculate power flows and therefore, various power grid constraints can be handled. It can handle, radial and meshed grids. The IEEE one-area reliability test system was used to validate the approach. Validated approach was applied to the real bnNETZE grid. The results presented show that they are scalable and replicable. Modelling accuracy for the grid, flexibilities are essential for the approach. In the future, market models should consider more robust load and optimal power flow approaches to address uncertainties in the forecasting. Additionally, the approaches need to be robust under faulty conditions with fallback scenarios, to prevent adverse grid settlements.

The usage of Matlab as a tool for simulation of large grids is not an efficient way as the simulation duration is very long. These approaches should be more developed in the future to consider the technical limitations of the electric grid especially of the DSOs as the network security is their main concern (n-1 calculation). Power quality, stability, and reliability of power supply constraints should be considered in the future. The usage of commercial simulation tools like PowerFactory allow the analysis and the observation of the grid different operation conditions and switching states, which should be considered also for the future planning of the DSOs to participate in the flexibility market without causing any congestions in the grid. More efficient cooperation between TSO and DSO is also very important and needed.

The experiments in this validation strand have proven the scalability and replicability of the proposed x-DLFM architectures. Still, there are many studies that still need to be made before these schemes can be implemented. More lessons learned and proposals for future studies regarding the DLFM architectures are found in [FleD53] (Table 33 in Section 5).

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