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

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Intermediate version of advanced market aware OPF algorithms

Deliverable D5.2

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Glossary of Acronyms

Project management terminology

Acronym	Definition
D	Deliverable
HLUC	High Level Use Case
MS	Milestone
WP	Work Package
UCS	Use Case Scenario

Technical terminology

Acronym	Definition
ATP	Automated Trading Platform
API	Automated Programming Interface
DB	Data Base
DESS	Distributed Energy Storage System
DG	Distributed Generation
DLEM	Distribution Level Energy Market
DLFM	Distribution Level Flexibility Market
DN	Distribution Network
DSO	Distribution System Operator
EC	European Commission
ESP	Energy Service Provider
FM	Flexibility Market
FMO	Flexibility Market Operator
FMCT	Flexibility Market Clearing Toolkit
FSP	Flexibility Service Provider
GenCo	Generation Company
GUI	Graphical User Interface
KER	Key Exploitable Result
KPI	Key Performance Indicator
LFM	Local Flexibility Market
LMO	Local Market Operator
LMP	Locational Marginal Price
MO	Market Operator
OPF	Optimal Power Flow
PC	Project Coordinator
PCC	Point of Common Coupling
RES	Renewable Energy Sources
SC	Steering Committee
SOB	Shared Order Book
SOC	State of Charge
SOCP	Second Order Cone Program
SVC	Static VAR Compensator

S/W	Software
TLMP	Transmission Locational Marginal Price
TN	Transmission Network
TSO	Transmission System Operator

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Document History

This deliverable includes the first version of the mathematical models, research problem formulations, algorithms and performance evaluation results for the operation of the FLEXGRID's flexibility market clearing toolkit.

Table 1: Document History Summary

Revision Date	File version	Summary of Changes
25/11/2020	v0.0	Draft ToC circulated within the entire consortium.
07/01/2021	v0.1	All partners commented on the draft ToC structure.
04/02/2021	v0.2	Final ToC version has been agreed and writing task delegations have been provided to all involved partners.
28/02/2021	v0.3	All partners contributed their 1st round inputs to the 1st draft version.
10/03/2021	v0.4	1st draft version has been compiled and reviewed by DTU.
16/03/2021	v0.5	All WP5 partners reviewed the 1st draft and sent their comments to DTU.
17/03/2021	v0.6	DTU addressed all comments from WP5 partners and sent the 2nd draft for internal review done by AIT.
22/03/2021	v0.7	AIT made a thorough review and requested for changes to enhance the quality of the deliverable.
24/03/2021	v0.8	DTU addressed all comments from the internal review process and forwarded the final version to the coordinator.
26/03/2021	Final	Coordinator (ICCS) made final enhancements/changes and submitted to ECAS portal

Executive Summary

This report is an official deliverable of the H2020-GA-863876 FLEXGRID project that describes the intermediate version of advanced market aware optimal power flow (OPF) algorithms developed within WP5. The focus of this document is on FLEXGRID High Level Use Case #1 (HLUC_01), which primarily focuses on network aware market clearing of distribution level flexibility markets (DLFM). Specifically, the algorithmic and modelling approach of Use Case Scenario UCS 1.1, UCS 1.2, and UCS 1.3 are detailed in this deliverable. The developed algorithms will be implemented in the Flexibility Market Clearing Toolkit (FMCT) of the FLEXGRID Automated Trading Platform (ATP). The intended user of the FMCT is the Flexibility Market Operator (FMO) on distribution network level.

Chapter 1 gives a brief introduction of the market design options and motivates the design choices. Chapters 2-4 follow a similar structure in order to present the WP5 research results in a coherent manner. In particular, for each one of the three UCS, we present:

- Problem statement, related state-of-the-art and summary of FLEXGRID contributions
- System model
- Problem formulation
- Algorithmic solution
- Simulation setup and performance evaluation results
- Next steps for research work until M26

The presented UCS 1.1, UCS 1.2, and UCS 1.3 are market clearing problem and thus the problem statements and algorithmic solutions are largely similar in Chapters 2-4. Chapter 2 addresses UCS 1.1, the “distribution network aware flexibility market clearing via FLEXGRID ATP”. To this end, a Distribution Level Energy Market (DLEM) clearing algorithm is presented that matches energy FlexOffers and energy FlexRequests, while respecting the physical network constraints. Chapter 3 addresses UCS 1.2, the “market-based local congestion management using FLEXGRID ATP in distribution networks using output from AC-OPF model calculation as dynamic input for ATP”. To this end, a Distribution Level Flexibility Market (DLFM) clearing algorithm is presented that matches active power reserve FlexOffers and active power reserve FlexRequests, while respecting the physical network constraints. Chapter 4 addresses UCS 1.3, the “market-based local voltage control using FLEXGRID ATP in distribution network operation”. To this end, a Distribution Level Flexibility Market (DLFM) clearing algorithm is presented that matches reactive power reserve FlexOffers and reactive power reserve FlexRequests, while respecting the physical network constraints. Chapter 5 discusses the possible DLFM integration with existing energy, reserve and near-real-time balancing markets. Chapter 6 presents the software (S/W) integration of the algorithms in the FMCT and the FLEXGRID ATP frontend (i.e. GUI). Chapter 7 summarizes the next steps for WP5 research work.

1 Introduction

1.1 Description of High-Level Use Case #1 and interaction with the FLEXGRID system as a whole

Flexibility Markets in the distribution grid shall be enabled to reduce grid enhancement costs and to enable better integration of renewable energies. The flexibility can therefore enhance the consumption in cases of high renewable infeed in the grid, e.g. PV. With the algorithms described in this deliverable, the design options for flexibility markets and respective mathematical algorithms of the Flexibility Markets shall be described and the simulation results are compared to identify the optimal design of flexibility markets. The market stakeholder operating these markets are Flexibility Market Operators (FMO). These FMOs are continuously designing new methods and solutions to support the activities of grid operations in the distribution grid.

In FLEXGRID, different design options of flexibility markets shall be developed for the efficient operation of these flexibility markets. Therefore, new advanced clearing models for the FMO's efficient market operation are developed, whereas the state-of-the-art of flexibility markets and the algorithms is described further in D2.1 [1]. The algorithms described in this deliverable are based on the high-level use cases of FLEXGRID. More details on the high level use cases of FLEXGRID can be found in detail in Section 4 of D2.1 [1], whereas the high level use case 1 (HLUC_01) is the most relevant for this deliverable.

HLUC_01 focuses on FLEXGRID ATP's operation and its interaction with incumbent markets, e.g. day-ahead wholesale market, and the underlying physical network operation. The initial idea is based on NODES business model in collaboration with Nord Pool Consulting (NPC) aiming at defining and developing advanced mathematical models and research algorithms to clear Distribution Level Flexibility Markets with consideration of physical network constraints. Three use case scenarios (UCS) are presented in this deliverable, see Table 2:

Table 2: Use Case Scenarios detailed in this deliverable

Nr.	Name	Goal of the Use Case	Lead
UCS_01	Distribution network aware flexibility market clearing via FLEXGRID ATP	The FMO wants to clear an energy market, i.e., DLEM, with Offers and Requests from different ESPs, while ensuring that the resulting power flows are feasible for the network.	DTU
UCS_02	Market-based local congestion management using FLEXGRID ATP in distribution networks using output from AC-OPF model calculation as dynamic input for ATP	The FMO wants to clear an active power reserve market, i.e., DLFM, with FlexOffers from the DSO and FlexRequests from different ESPs, while ensuring that the resulting power flows are feasible for the network.	DTU
UCS_03	Market-based local voltage control using FLEXGRID ATP	The FMO wants to clear a reactive power reserve market, i.e., DLFM, with	DTU

	in distribution network operation	FlexOffers from the DSO and FlexRequests from different ESPs, while ensuring that the resulting power flows are feasible for the network.	

1.2 Summary of state-of-the-art solutions for the market clearing challenges

The aim of market clearing is to establish operating points for all market players that try to maximize some objective, commonly social welfare. Optimal power flow (OPF) is used to run a network-aware market clearing that considers the distribution network with its line limitations, voltage bounds, and transformer limits. The OPF can determine how much flexibility can be cleared safely without violating network constraints.

Different types of OPF exist; the most accurate is a full AC-OPF which captures all relevant network quantities, including reactive power, losses, voltages and voltage angles. However, the AC-OPF is a non-convex problem, which implies that the global optimum is not guaranteed to be found. Therefore, the scientific literature has developed several approximations of the full AC-OPF.

The simplest approximation is the DC-OPF which ignores voltage magnitude, reactive power and losses, but results in a linear problem which is easy to solve. More accurate approximations are e.g. the BranchFlow method or the LinDistFlow, which are second order cone programming (SOCP) relaxations of the AC-OPF. The mathematical formulation is found in section 2.3.

The main idea here is to use a convex relaxation of the AC-OPF, including line constraints, losses, voltage and reactive power. This model will be general enough so that it can be used for different applications (market clearing, identification of flexibility needs by the DSO, verification of a given dispatch).

We carried out a comparison of different SOCP formulations in [2]. Among the methods compared, the one introduced in [3] showed the most promising results for active distribution grids and general radial network, so it is the chosen approach here. The AC-OPF is first augmented with additional constraints and then relaxed. The objective function can be adjusted depending on the intended use of the model:

- Minimization of the costs (or maximization of the social welfare)
- Minimization of voltage deviations
- Minimization of congestions
- Empty objective function to evaluate the feasibility of a given dispatch

This model can be enhanced to help decision making for the DSO, by including the possibility to cut off some users in case of infeasible dispatch. This is modelled by adding slack variables in the constraints for line capacity and voltage limits, associated with a high penalty cost in the objective function.

1.3 Summary of research problems and FLEXGRID's research innovation

Following up the survey work mentioned above from both academic and industrial perspectives, we have come up with three main related FLEXGRID research problems:

1) The FMO wants to efficiently clear a (set of) FlexRequests and FlexOffers for energy that maximize social welfare while taking into account network constraints (cf. UCS 1.1)
2) The FMO wants to efficiently clear a (set of) FlexRequests and FlexOffers for active power reserve that maximize social welfare while taking into account network constraints (cf. UCS 1.2)
3) The FMO wants to efficiently clear a (set of) FlexRequests and FlexOffers for reactive power reserve that maximize social welfare while taking into account network constraints (cf. UCS 1.3).

The main research problem addressed in this deliverable is the inclusion of physical network constraints into the market clearing. To approach this problem, a variety of network modelling choices, as well as market design choices have to be made. There exist several design choices that affect the modelling and ultimately the efficiency of the market. An overview about relevant design parameters is listed in [4], the relevant parameters that are important for the FLEXGRID algorithm are described here.

Auction vs. Continuous Clearing: A part of the flexibility market clearing could be auction based such as day-ahead flexibility market, using the AC-OPF as presented in Section 3.1 of D5.1 [5]. However, moving closer to real-time, it could become more relevant to have a continuous market. Instead of a market clearing considering all bids and clearing once and for all, this model would be continuously matching bids. This is often the case for intraday markets.

Pay-as-bid (discriminatory pricing) vs. Pay-as-clear (uniform pricing): In continuous trading, pay-as-bid is the only available pricing mechanism. It matches FlexOffers and FlexRequests, if the offer price is lower than or equal to the request price. In that case, the bid that was placed earliest sets the price. With the uniform pricing rule, all participants in a given price zone are cleared with pay-as-clear, i.e., all participants receive the same market clearing price (MCP). In auctions, both types of pricing mechanisms are possible.

Technology Neutrality and Market Horizon: Today, the central market displays various types of market horizons; from futures and forwards (10 years) to real-time (5min) markets, and ex-post (1-14 days after delivery) settlement. Long-term procurement, i.e. a year or longer, would facilitate the planning and investment process of distribution system operators. Short-term procurement, however, would promote the access of small scale flexible loads and variable renewable energy sources to participate in the market.

Product Standardization: In the highly liquid wholesale markets (day-ahead and intraday), standardized products are traded today; energy per unit of time, e.g. MWh/h. However, with the event of allowing block bids, the standardization has suffered. On the extreme ends, a market cannot trade fully standardized products only, or trade any possible sub-characteristic of bids. Naturally, a standardized product would achieve higher liquidity. On the other hand, non-standardized products may give special incentives to, e.g. superfast ramping resources or resources in an effective location in the grid, which is related to the following point.

Locational Tagging: With the consideration of network constraints, the location of a Flexibility Service Provider (FSP)[1] becomes a vital characteristic. It may decide whether the FSP's bid has a higher effectiveness to solve a grid problem and therefore, it is cheaper to solve a grid problem with a flexibility that is in a favorable location. An unfavorable location of the resource could even lead to disqualification of the resource due to infeasible power flows. The more local, and therefore closer to the arising problem, a grid problem is solved, the more effective the solution would be. The disadvantage of high locational resolution is that local market power may be exploitable (as for example shown in [6]). On the other hand, the larger the zone, the more liquidity and competition can be expected.

Summary and Justification: An illustration of the discussed market design choices is shown in Figure 1. In the scope of D5.2, we focus on two extremes of the design space: a uniform price auction (UPA) of standardized products on the one end, and a discriminatory continuous (CPAB) clearing of non-standardized products on the other end (circled in blue). We include a location tag in the bids, but allow bids from different locations to match, as long as these transaction do not violate network constraints (i.e., if they pass the network check detailed in section 2.4). We do not impose strong assumptions on the market horizon. Based on the literature, e.g. [3], we recommend to use auction for longer market horizons and continuous clearing for shorter market horizons.

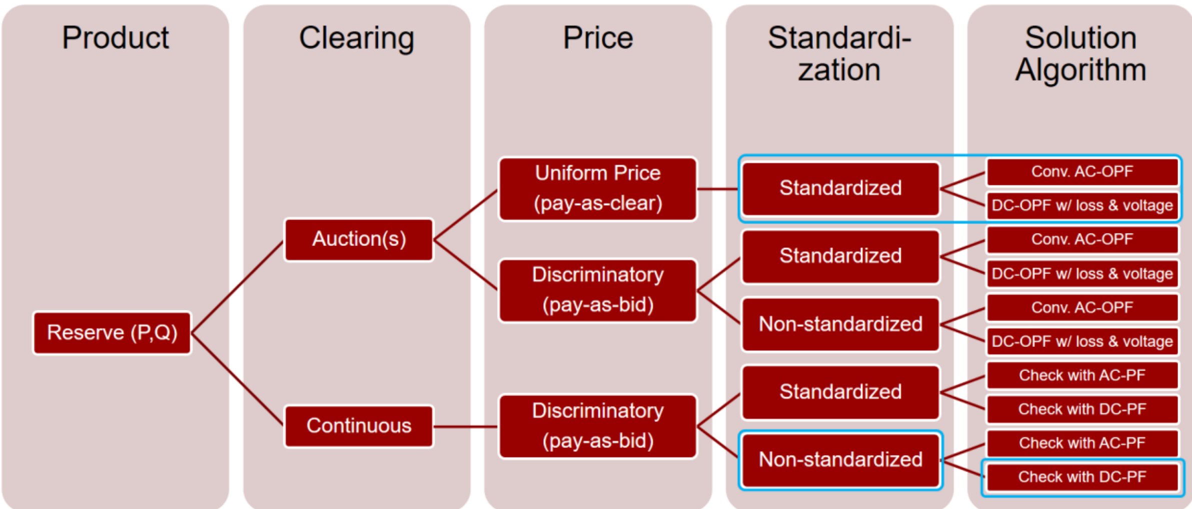

Figure 1: Summary of market design choices

The solution algorithms are explained in Error! Reference source not found.**,** Error! Reference source not found.**, and** Error! Reference source not found.**. This deliverable focuses on *continuous market clearing algorithms* for energy (UCS 1.1 in** Error! Reference source not found.**) and reserve (P-reserve in UCS 1.2 in** Error! Reference source not found.**, and Q-reserve in UCS 1.3 in** Error! Reference source not found.**). Deliverable D5.3 will cover *auction based market clearing* algorithms for these three use case scenarios.**

[1] We use the term FSP in this deliverable as a general term to represent the FlexSupply side of the proposed Distribution Level Flexibility Markets (DLFM).

1.4 Summary of FLEXGRID's research impact on today and future market operator business

FLEXGRID will develop advanced market clearing models and algorithms for the proposed Distribution-Level Flexibility Markets (DLFM). Sophisticated AC-OPF models will be developed, which aim at producing effective market signals to FlexSuppliers using locational information and ensuring feasible power flows.

1.5 Scope of this Deliverable

This document provides an intermediate description of the network-aware market clearing algorithms for DLFM. The final version of market clearing algorithms will be published in Deliverable D5.3.

This deliverable is intermediate in the sense that it focuses on continuous market clearing algorithms for energy (UCS 1.1 in Chapter 2) and reserve (P-reserve in UCS 1.2 in Chapter 3, and Q-reserve in UCS 1.3 in Chapter 4). Deliverable D5.3 will then focus on auction based market clearing algorithms for these three use case scenarios.

1.6 Structure of this Deliverable

This document provides an intermediate description of the network-aware market clearing algorithms for DLFM that clears energy (chapter 2, UCS 1.1), active power reserves (chapter 3, UCS 1.2) and reactive power reserves (chapter 4, UCS 1.3). It further provides possible integration approaches of the x-DLFM into existing markets in chapter 5. Chapter 6 details the backend FMCT and GUI. A brief conclusion is provided in chapter 7.

2 UCS 1.1 - Distribution network aware flexibility market clearing via FLEXGRID ATP

The focus of this chapter is the research problem of FLEXGRID's HLUC_01_UCS_01. In this specific Use Case Scenario (UCS), the FMO needs to clear a continuous DLEM under consideration of network constraints.

2.1 Problem statement, related state-of-the-art and FLEXGRID research contributions

The existing electricity markets do not consider the constraints of local distribution networks, leading to a sub-optimal use of these networks. As the penetration of distributed energy resources connected to the distribution network increases, it becomes necessary to consider the creation of a market which takes into account the distribution networks, their constraints, and the location of the flexible resources. This could in turn drive down the costs for the whole system, and enable the integration of renewable energy sources, while providing an alternative to distribution network upgrade.

One way to deal with a high penetration of distributed energy resources is to implement a local energy market. In the literature, we can find three groups of local energy markets [7]:

- Peer-to-peer (P2P) markets [8]
- Centralized markets, run by a flexibility market operator (FMO) [9]
- Markets where participants can either trade directly among each other or through a FMO [10]

It is easier to consider the network constraints in a centralized approach, where only the FMO has access to the information about the network parameters. The integration of distribution network constraints is necessary, in particular to ensure that line congestions and voltage deviations are avoided. However, at distribution level, the DC Power Flow approximation is not as accurate anymore as on transmission level. An AC Power Flow, on the other hand, gives an exact representation of such system, at the cost of non-linear equations. For these reasons, FLEXGRID considers approximations that provide a suitable trade-off between computational complexity and a satisfying representation of the line flows. In particular, it is essential to include both active and reactive power.

There has been a lot of interest for convex relaxation of AC-OPF in the last years. Detailed surveys are available in [11], [12], and [13]. Some widely used relaxations are:

- Semi-Definite Programming (SDP)
- Quadratically Constrained Programming (QC), a particular case of SDP
- Second Order Cone Program (SOCP), a particular case of QC

There is generally a trade-off between the tightness of the relaxation (i.e., how small the resulting superset is) and the computational time. In practice, time limits are dictated by the respective market gate closure time and clearing price announcement. SDP and QC are tighter than SOCP but they take longer to solve [14] [15] [16] [17].

In FLEXGRID, we focus on the DSO role in the local market to avoid congestions and voltage deviations. The novelty of the FLEXGRID's approach is that the FMO clears the market under full consideration of network constraints, i.e., including line and transformer ratings, reactive power limits, and voltage bounds. Moreover, the active participation of the DSO is considered with a continuous market setup.

2.2 System model

In this UCS, we consider a Flexibility Market Operator (FMO), who clears a local energy market after (i.e. R-DLEM) the transmission level commitments have been cleared. This means that some of the local generators and loads may already have committed parts of their energy to the wholesale transmission level (i.e. day-ahead energy market). The FMO runs a market where FlexRequests and FlexOffers are matched, provided that no distribution network constraint is violated. Without loss of generality and within FLEXGRID's context, we assume that the full network model of the DSO is known to the FMO, as well as the active and reactive power setpoints committed in the wholesale transmission level market. The aim of the FMO is to maximize social welfare by matching all bids that result in feasible power flows.

As shown in Figure 2, two setups are considered:

- A continuous pay-as-bid market clearing algorithm
- An auction-based pay-as-clear market clearing algorithm

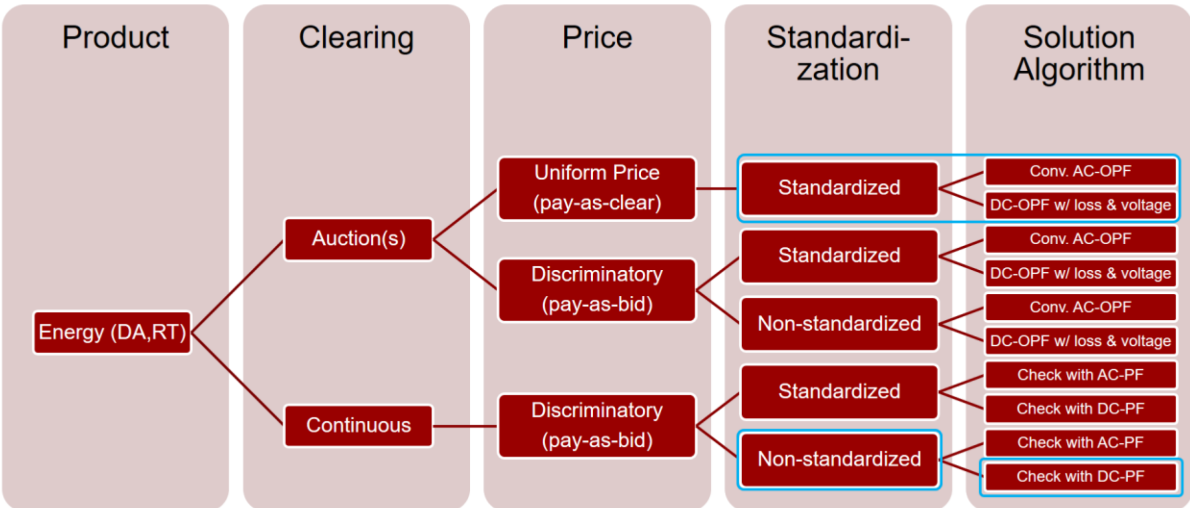

Figure 2: Market design choices for distribution level energy market (DLEM)

2.3 Problem Formulation

2.3.1 Bids

Actors submit a bid as FlexRequest (from the DSO) or FlexOffer (from the FSP) for energy in MWh/h in either upward (generation increase / demand decrease) or downward (generation decrease / consumption increase) direction.

The bid is composed of:

- Nature: FlexOffer or FlexRequest
- Direction: up or down
- Price
- Volume
- Location ID: network bus
- Time target: for which time period(s) the bid applies
- Time stamp: indicates when the bid was submitted

2.3.2 Shared Order Book

Incoming, non-matching bids are placed in a shared order book (SOB), available to all market participants, until they are cleared with a matching bid. There is one SOB for FlexRequests and one for FlexOffers and is visible by both DSO and ESPs. They contain all the details of the bids and are sorted:

- By price first. For FlexRequests the bid with the highest price comes first and for FlexOffers, the bid with the lowest price comes first.
- By time stamp then. For two bids with the same price, the oldest comes first.

2.3.3 Matching

Bids are matched according to price, time-priority and the absence of line congestions. The matching algorithm has the following heuristic properties:

- Automatic process: It is triggered when a bid is added or updated
- Pay-as-bid pricing: Each participant gets the price of the earliest bid of the two matching bids.
- Best price: A FlexRequest can only match with a FlexOffer with a price that is inferior or equal. If several orders meet this requirement, the priority goes to the one with the best price (highest price for a FlexRequest and lowest price for a FlexOffer).
- First-come-first- served principle: If there are two orders with the same price, the priority goes to the one that was submitted first.
- Network check: A network check is performed to ensure that the activation of the bids would not result in congestions
- Partial execution: If an order is only partially matched, the rest of the bids stays or goes to the corresponding SOB. Owing to the network check requirement, it is especially important to allow partial matching of the bids. In this way, we can make sure that two bids can match up to the point where their activation would result in a congestion.

It is vital to note that the location of the bids does not need to match, i.e., FlexOffer and FlexRequest can be located at different buses.

2.3.4 Network Check

The network check is based on a baseline energy dispatch that is established by either previous markets (e.g., day-ahead energy market) or by an estimation of load and generation at each bus (based on, e.g., usually available data of similar days and hours and load forecasting). The network check has the following characteristics:

Network Model:

- **DC power flow:** We have used the DC power flow algorithm as the first step towards the inclusion of network constraints in a continuous market clearing algorithm. Two main reasons for this choice are that the DC power flow is simpler, and thus more transparent for the market players, and faster, with computing time being a critical element for continuous markets.
- **Convexified AC power flow approximations, e.g. LinDistFlow, BranchFlow:** Other models will be considered later.

2.3.5 Multi-period model

Several time targets can be accessed at any point in time. Each bid must specify to which session it is submitted. In D5.3, this approach will be extended to capture block-bids, which cover more than one session and require complete matching.

2.3.6 Quantity update algorithm with DC Power Flow

With DC power flow, the power flows are calculated with the help of the power transfer distribution factors (PTDFs). PTDFs are linear sensitivities linking power injections with line flows (for more details about their calculation, see [18]). PTDFs are fixed for a given network. In particular, the power flow in the line between bus i and j, P_{ij} , is linked to the power injected at bus m, P_m, by the PTDF factor of line ij for an injection of power at the slack bus k and retrieval of the same quantity in bus m, $PTDF_{ij,km}$ by:

$$P_{ij} = X_m PTDF_{ij,km} P_m \tag{2.1}$$

The maximum power flow variations, in both directions, can then be evaluated as:

$$\Delta P_{ij}^{max,+} = P_{ij}^{max} - P_{ij} \tag{2.2}$$
$$\Delta P_{ij}^{max,-} = -P_{ij}^{max} - P_{ij} \tag{2.3}$$

where $\Delta P_{ij}^{max,+}$ and $\Delta P_{ij}^{max,-}$ are the maximum power flow variations respectively from i to j and from j to i, and P_{ij}^{max} is the line capacity. Finally, we use that the change in the power flow of line ij associated with a power injection at bus m and equivalent withdrawal at n can be obtained as:

$$\Delta P_{ij} = \left(PTDF_{ij,kn} - PTDF_{ij,km}\right)\Delta P_{mn} \tag{2.4}$$

The following algorithm describes how to evaluate the maximum quantity that can be traded for an injection in bus m and retrieval in bus n:

```
Data: request_bus, offer_bus, Quantity
if up_regulation then
       m = offer_bus;
       n = request_bus;
else if down_regulation then
       m = request_bus;
```

n = offer_bus;
for all the lines ij in the distribution system **do**
Calculate $P_{ij} = X_m PTDF_{ij,km} P_m$
Calculate $\Delta P_{ij}^{max,+} = P_{ij}^{max} - P_{ij}$
Calculate $\Delta P_{ij}^{max,-} = -P_{ij}^{max} - P_{ij}$
Calculate Quantity_max that can be injected in bus m and retrieved in bus n, taking into account the direction of the flow: $\Delta P_{mn}^{max} = \frac{(PTDF_{ij,kn} - PTDF_{ij,km})}{\Delta P_{ij}^{max}}$
Update Quantity to be lower than or equal to Quantity_max;
return Quantity

2.4 Algorithmic solution

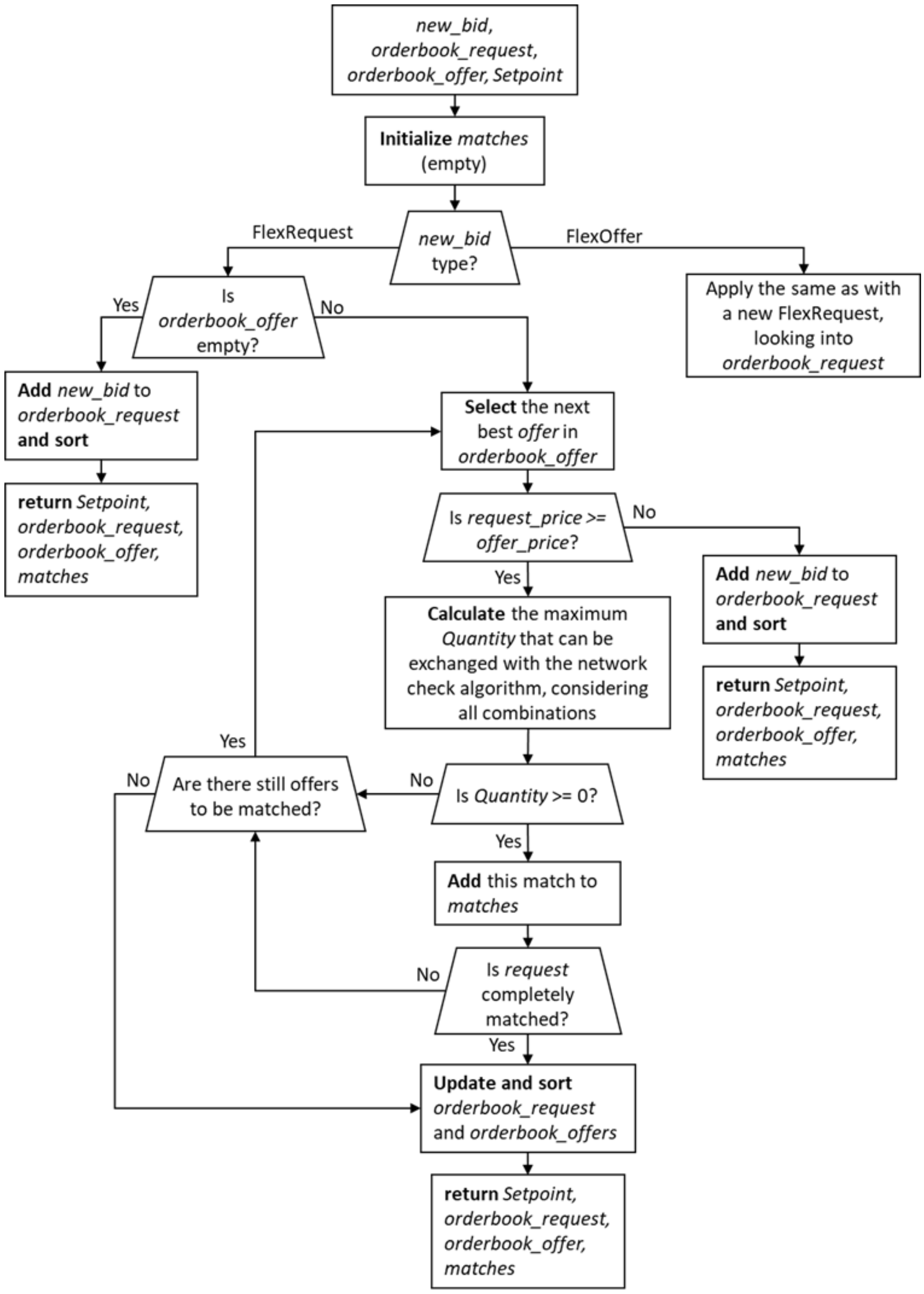

Figure 3: Heuristic approach to the continuous market clearing of DLEM in UCS 1.1

Finally, an incoming bid is matched following the algorithm given on next page. In case of a match with an unconditional request, the matching algorithm runs again on the bids in the SOBs.

2.5 Simulation setup and performance evaluation results

2.5.1 Simulation setup

The inputs needed by the market clearing algorithms are:

- The network data (including topology, line constraints, impedances…)
- An initial setpoint (net power injections for each bus of the system) obtained from previous commitments towards the wholesale market. (If there are no preceding commitments and markets, the setpoints are zero.)
- The bids (including all the relevant characteristics)
    - For the continuous matching algorithm, this includes the new bid and the SOBs for requests and offers.

The outputs are:

- Accepted bids with volume, location and price
- Market price(s)
- The social welfare, calculated as the difference between the utility of the accepted FlexRequests and the cost of the accepted FlexOffers (assuming that all participants bid their true utility/cost).
- The flexibility procurement cost, which corresponds to the DSO expense in the flexibility market and is obtained using the market price.

For the continuous market, the information about matches are gathered in a table. An example is shown below:

Table 3: Example of matches in UCS 1.1

Offer ID		Offer Bus	Request ID	Request Bus	Direction	Quantity	Matching Price	Time target
Offer1		Bus1	Request3	Bus15	Up	0.01	39	1000-1100
Offer2		Bus4	Request6	Bus6	Down	0.03	38	0900-1000

2.5.2 Performance evaluation and KPIs

The principal goal of this research problem is the maximization of social welfare which comprises the welfare of FlexSuppliers (ESP/FSP) and FlexBuyers (DSO). In order to evaluate the performance of the proposed algorithm, the following KPIs listed in Table 4 will be measured.

Table 4: Key performance indicators for UCS 1.1

KPI	Description

Tightness of the relaxation	Largest relaxed constraint residual over the test period (only for auction based clearing)
Exactness of the relaxation	The optimal solution is feasible for the AC-OPF (only for auction based clearing)
Optimality gap	Gap between the value of the objective function of the AC-OPF at the optimal solution and the value of the objective function of the relaxed AC-OPF at the optimal solution (only for auction based clearing)
Total computational runtime	How long it takes for the algorithm to return results. It should stay below a defined threshold.

The KPIs to be used for the design of the flexibility market are gathered in Table 5.

Table 5: KPIs for the design of the DLEM in UCS 1.1 market

KPI	Description
Social Welfare	Difference between how the actors value flexibility and the money they get for it.
Flexibility procurement cost	Cost of flexibility for the DSO
Curtailment	Total reduction in the amount of energy due to line congestions
Cost reduction achieved	Difference in cost with implementing a reinforcement of the network instead of having flexibility markets

2.6 Next research steps for M19-M26 period

During the period M19-M26 of the FLEXGRID project, the focus of this research problem will be on the following actions:

- Implement an auction-based energy market
    - Use a more accurate, convex approximation of the AC-OPF to clear the market, e.g. LinDistFlow.
    - Study how to retrieve relevant market prices
    - Expand the model to include block bids
- Complete the study on the continuous framework
    - Implement more accurate, convex approximation of the AC power flow as the network check method
- Include the calculation of all required KPIs
- Integrate algorithms in the FLEXGRID ATP

3 UCS 1.2 - Market-based local congestion management using FLEXGRID ATP in distribution networks using output from AC-OPF model calculation as dynamic input for ATP

This chapter deals with the research problem of FLEXGRID's UCS 1.2. In this UCS, we consider the problem of an FMO that wants to clear a DLFM with active power reserve bids to manage local congestions in the distribution network.

3.1 Problem statement, related state-of-the-art and FLEXGRID research contributions

The increasing penetration of distributed energy resources motivates the creation of new market tools aimed for the DSO. Having access to the active power flexibility of those distributed resources would enable DSOs to operate their networks in a more secure manner, by reducing the occurrence of line congestions through the activation of flexibility. To do so, the network constraints must be included in the model. Usual modeling approaches either ignore the network [19] [20] [21] [22], or if they include the local flexibility scheduling in distribution power flow calculations, they assume that the DSO and the FMO form one entity [23] [24] [25] [26]. In that case, decisions about flexibility procurement and activation are made considering requirements of DSO to solve congestion issues. However, the legal framework may (and, in the EU, currently does) not allow the DSO to act as the market operator.

Regarding the trading type, two main options will be covered:

- Continuous matching of the bids, in this Deliverable D5.2
- Auction-based market clearing, in the following Deliverable D5.3

In the context of FLEXGRID, we propose both an auction-based DLFM targeted at day-ahead and earlier markets, and a continuous market clearing algorithm targeted at real-time markets, with the FMO being a separate agent in both cases. The conceptual design of a DLFM that is cleared by an independent FMO entity and that explicitly considers network constraints is a novelty.

3.2 System model

In this UCS, we consider a Flexibility Market Operator (FMO), who clears a local *active* power *reserve* market after (R-DLFM) the transmission level commitments have been cleared. This means that some of the local generators and loads may already have committed parts of their energy and/or reserve to the wholesale transmission level. The FMO runs a continuous pay-as-bid market where FlexRequest from the DSO and FlexOffers from FSPs are continuously accepted and added to the orderbook. When the prices match, a network check is performed in order to ensure that no network constraint is violated. Without loss of generality and within FLEXGRID's context, we assume that the full network model of the DSO is known to the FMO, as well as the active and reactive power setpoints committed in the wholesale transmission level market. The aim of the FMO is to maximize social welfare by matching all bids that result in feasible power flows. An auction-based market clearing algorithm (i.e. pay-as-clear) will also be available for deliverable D5.3. In this algorithm, the FMO will gather all FlexRequests and FlexOffers for a given timeframe. At gate closure, no further bids will be accepted and the network-aware auction-based market clearing algorithm will run. The different algorithms are shown in Figure 4.

Here, the novelty of FLEXGRID's algorithmic approach is that the FMO clears the market continuously and under full consideration of network constraints, i.e., including line and transformer ratings, reactive power limits, and voltage bands. A second contribution is that this algorithm ensures that any combination of reserve activation is feasible for the network, opposed to current approaches, where one feasible reserve activation suffices.

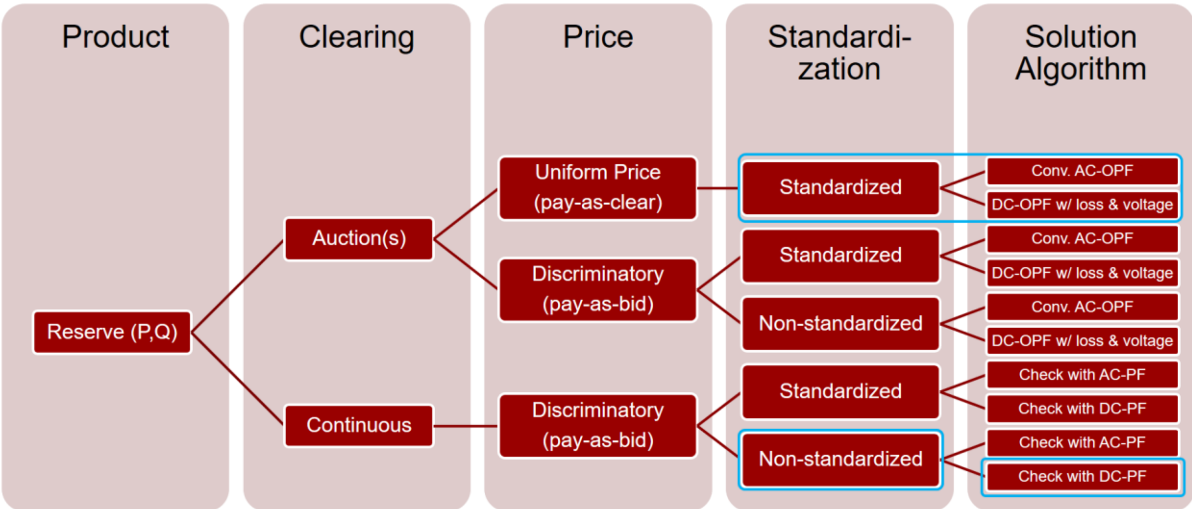

Figure 4: Market design choices for UCS 1.2 reserve distribution level flexibility market (DLFM)

3.3 Problem Formulation

The FMO that aims to clear the DLEM, while ensuring a feasible operating point for the distribution network (DN). For this, the DSO must provide crucial network data. The task of the FMCT is to find feasible market transactions that respect the physical limits of the DN, while maximizing social welfare within the given network constraints.

3.3.1 Bids

Actors submit a bid as FlexRequest or FlexOffer for active power reserve capacity (availability) in either upward or downward direction.
The bid is composed of:

- Nature: FlexOffer or FlexRequest

- Type: (for a FlexRequest) , i.e., Conditional or Unconditional
- Direction: up or down
- Price
- Volume
- Location ID: (network bus)
- Time target: for which time period it applies
- Time stamp: indicating when the bid was submitted

FlexRequests can specify whether they are conditional or unconditional. Market actors seem to be in a position to estimate whether their FlexRequest will be activated in the real-time operation with high probability (certainty) or not. A request tagged as unconditional is expected to be activated with certainty, unlike a request tagged as conditional.

3.3.2 Shared Order Book

Incoming, non-matching bids are placed in a shared order book (SOB) until they are cleared with a matching bid. There is one SOB for FlexRequests and one for FlexOffers. They contain the all the details of the bids and are sorted:

- By price first. For FlexRequests the bid with the highest price comes first and for FlexOffers, the bid with the lowest price comes first.
- By time stamp then. For two bids with the same price, the earliest comes first.

3.3.3 Matching

Bids are matched according to price, time-priority and the absence of line congestions. The matching algorithm has the following properties:

- **Automatic process**: It is triggered when a bid is added or updated
- **Pay-as-bid pricing**: Each participant gets the price of the oldest bid of the two bids matching.
- **Best price**: A FlexRequest can only match with a FlexOffer with a price that is lower or equal. If several orders meet this requirement, the priority goes to the one with the best price (highest price for a FlexRequest and lowest price for a FlexOffer).
- **First-come-first-served principle**: If they are two orders with the same price, the priority goes to the one that was submitted first.
- **Network check**: A network check is performed to ensure that the activation of the bids would not result in congestions
- **Partial execution**: If an order is only partially matched, the rest of the bid remains or goes to the corresponding SOB. Owing to the network check requirement, it is especially important to allow partial matching of the bids. In this way, we can make sure that two bids can match up to the point where their activation could result in a congestion.

It is vital to note that the location of the bids does not need to match, i.e., FlexOffer and FlexRequest can be located at different buses.

3.3.4 Network Check

The network check is based on a baseline energy dispatch that is established by either previous markets (e.g., day-ahead energy market) or by an estimation of load and generation at each bus (based on, e.g., usually available data of similar days and hours and load forecasting). The network check has the following characteristics:

- Network Model:
    - **DC power flow:** We have used the DC power flow algorithm as the first step towards the inclusion of network constraints in a continuous market clearing algorithm. Two main reasons for this choice is that the DC power flow is simpler, and thus more transparent for the market players, and faster, with computing time being a critical element for continuous markets.
    - **Convex approximations of AC power flow, e.g. LinDistFlow:** Other models will be considered later.
- Check Procedure: When designing the network check algorithm, one has to keep in mind that this is a market for flexibility reserves. There is no guarantee that the procured reserves will be activated, but we need to make sure that they can be activated without causing any congestion. A discussion on how to achieve feasible solutions at both the market clearing stage and during real-time activation is available in [27]. Several setups can be considered but the only way to make sure that the activation would not lead to line congestions is to test the activation of all combinations of accepted bids with the new bid under check.
- Unconditional Requests: The bids in the order book are re-evaluated once unconditional requests are matched, as they modify the power dispatch.

3.3.5 Multi-Period Model

Several market sessions can be accessed at any point in time. Each bids must specify to which session it is submitted. This later allows for block-bids, covering more than one session and requiring complete matching.

3.3.6 Quantity update algorithm with DC Power Flow

Assuming DC power flow, the power flows are calculated with the help of the power transfer distribution factors (PTDFs). PTDFs are linear sensitivities linking power injections with line flows (for more details, see [18]). In particular, the power flow in the line between bus i and j, P_{ij} , is linked to the power injected at bus m, P_m, by the PTDF factor of line ij for an injection of power at the slack bus k and retrieval of the same quantity in bus m, $PTDF_{ij,km}$ by:

$$P_{ij} = X_m PTDF_{ij,km} P_m \tag{3.1}$$

The maximum power flow variations, in both directions, can then be evaluated as:

$$\Delta P_{ij}^{max,+} = P_{ij}^{max} - P_{ij} \tag{3.2}$$
$$\Delta P_{ij}^{max,-} = -P_{ij}^{max} - P_{ij} \tag{3.3}$$

where $\Delta P_{ij}^{max,+}$ and $\Delta P_{ij}^{max,-}$ are the maximum power flow variations respectively from i to j and from j to i, and P_{ij}^{max} is the line capacity. Finally, we use that the change in the power flow of line ij associated with a power injection at bus m and equivalent withdrawal at n can be obtained as:

$$\Delta P_{ij} = (PTDF_{ij,kn} - PTDF_{ij,km})\Delta P_{mn} \tag{3.4}$$

The following algorithm describes how to evaluate the maximum quantity that can be traded for an injection in bus m and retrieval in bus n:

```
Data: request_bus, offer_bus, Quantity
if up_regulation then
      m = offer_bus;
      n = request_bus;
else if down_regulation then
      m = request_bus;
      n = offer_bus;
for all the lines ij in the distribution system do
      Calculate P_ij = X_m PTDF_ij,km P_m
      Calculate ΔP_ij^max,+ = P_ij^max − P_ij
      Calculate ΔP_ij^max,− = − P_ij^max − P_ij
      Calculate Quantity_max that can be injected in bus m and retrieved
      in bus n, taking into account the direction of the flow: ΔP_mn^max =
      (PTDF_ij,kn − PTDF_ij,km) / ΔP_ij^max
      Update Quantity to be lower than or equal to Quantity_max;
return Quantity
```

3.4 Algorithmic solution

Finally, an incoming bid is matched following the algorithm depicted in Figure 5. In case of a match with an unconditional request, the matching algorithm runs again on the bids in the SOBs.

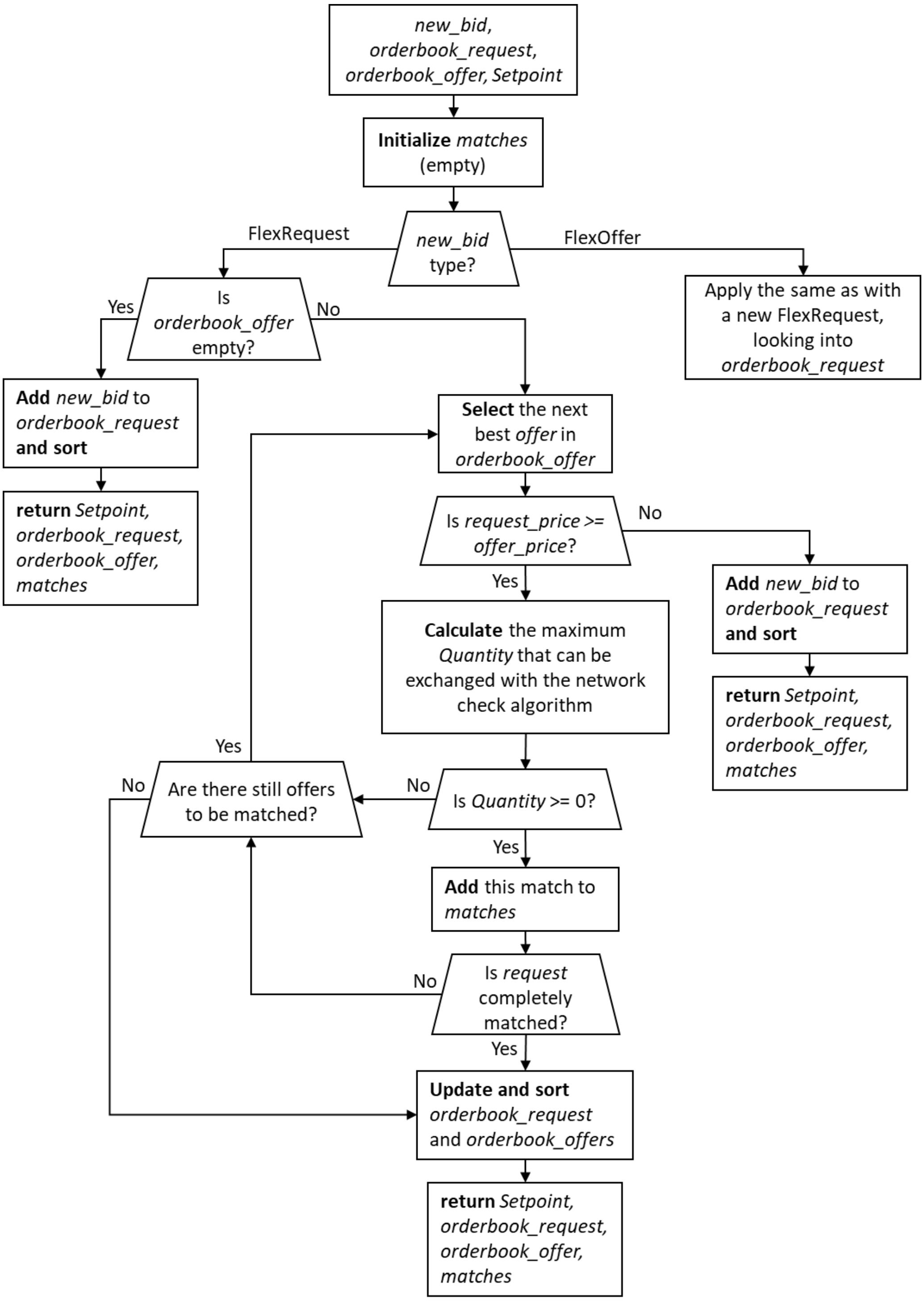

Figure 5: Heuristic approach to the continuous active power reserve DLFM clearing in UCS 1.2

3.5 Simulation setup and performance evaluation results

3.5.1 Simulation setup and evaluation framework

The inputs needed by the market clearing algorithms are:

- The network data (including topology, line constraints, impedances…)

- An initial setpoint (net power injections for each bus of the system) obtained from previous commitments towards the wholesale market. (If there are no preceding commitments and markets, the setpoints are zero.)
- The bids (including all the relevant characteristics)
    - For the continuous matching algorithm, this is the new bid and the SOBs for requests and offers.

The outputs are:

- Accepted bids with level
- Market price(s)
- The social welfare, calculated as the difference between the utility of the accepted FlexRequests and the cost of the accepted FlexOffers (assuming that all participants bid their true utility/cost).
- The flexibility procurement cost, which corresponds to the DSO expense in the flexibility market and is obtained using the market price.

For the continuous market, the information about matches are gathered in a table. An example is shown in Table 6.

Table 6: Example of matches in UCS 1.2

Offer ID	Offer Bus	Request ID	Request Bus	Direction	Quantity	Matching Price	Time target
Offer1	Bus1	Request3	Bus15	Up	0.01	39	1000-1100
Offer2	Bus4	Request6	Bus6	Down	0.03	38	0900-1000

3.5.2 Performance evaluation results

The KPIs to be used for the performance of the algorithms are summarized in Table 7.

Table 7: Key Performance indicators in UCS 1.2

KPI	Description
Tightness of the relaxation	Largest relaxed constraint residual over the test period (only for auction based clearing)
Exactness of the relaxation	The optimal solution is feasible for the AC-OPF (only for auction based clearing)
Optimality gap	Gap between the value of the objective function of the AC-OPF at the optimal solution and the value of the objective function of the relaxed AC-OPF at the optimal solution (only for auction based clearing)
Total computational runtime	How long it takes for the algorithm to return results. It should stay below a defined threshold.

The KPIs to be used for the design of the flexibility market are gathered in Table 8.

Table 8: KPIs for the design of the flexibility market in UCS 1.2

KPI	Description
Social Welfare	Difference between how the actors value flexibility and the money they get for it.
Flexibility procurement cost	Cost of flexibility for the DSO
Curtailment	Total reduction in the amount of energy due to line congestions
Cost reduction achieved	Difference in cost with implementing a reinforcement of the network instead of having flexibility markets

3.6 Next research steps for the M19-M26 period

Within M19-M26, we will elaborate on the UCS 1.2 work and the following actions will be undertaken:

- Implement an auction-based reserve market
    - Use a more accurate, convex approximation of the AC-OPF to clear the market, e.g. LinDistFlow.
    - Study how to retrieve relevant market prices
    - Expand the model to include block bids.
- Complete the study on the continuous framework
    - Implement a more accurate, convex approximation of the AC-PF, e.g. the BranchFlow method as network check
- Include the calculation of all required KPIs
- Integrate algorithms in the FLEXGRID ATP

4 UCS 1.3 - Market-based local voltage control using FLEXGRID ATP in distribution network operation

This chapter deals with the research problem of UCS 1.3. In FLEXGRID, we propose a novel reactive (and active) power reserve DLFM clearing algorithm that clear continuously, while considering network constraints.

4.1 Problem statement, related state-of-the-art and FLEXGRID research contributions

Active and reactive power flexibility in distribution networks will offer the distribution system operators more robust control over the network's voltage violation and line congestion. However, the market-clearing algorithm using DC power flow equation discussed in Chapter 3 is not able to incorporate reactive power flow or voltage magnitude into the formulation. Day-ahead active and reactive power flexibility markets was discussed in [28] [29] [30] [19]. However, these models use a nonlinear formulation for distribution network constraints, and they are not efficient for continuous market clearing algorithms. Nonlinear approaches require higher computational effort, and thus time, without guarantees of finding an optimal solution.

A new market clearing algorithm is proposed in this chapter to overcome this limitation, which uses Liniearized Distribution Flow (LinDistFlow) [31] for checking network constraints. The proposed algorithm can be used for both continuous market clearing algorithms targeted at real-time markets and auction-based market clearing. Like the model proposed in chapter three, this algorithm will also consider network constraints like voltage violation and network congestion and also ensure that any combination of reserve activation is feasible in the network.

4.2 System model

It is assumed here that the flexibility market clearing occurs after the transmission level commitments have been cleared (R-DLFM), because it is compatible with the existing EU regulatory framework. Thus, the real and reactive power demand and generation setpoint for each timestep is available to the FMO. We also assume that the network model, voltage and line constraints are available to the FMO when running the market clearing algorithm.

In the real-time continuous market clearing algorithm, when a new FlexRequest from DSOs or FlexOffer from FSPs arrives, the FMCT looks for a possible match in the existing order book. Once a match occurs, the market clearing algorithm carries out a network check to rule out the possibility of a network constraint violation. This process is carried out continuously by the FMCT, and all the unmatched requests and offers will be added to the respective order book. An auction-based market clearing algorithm (i.e., pay-as-clear) will also be discussed in D5.3. An overview of different market design options is given in Figure 6.

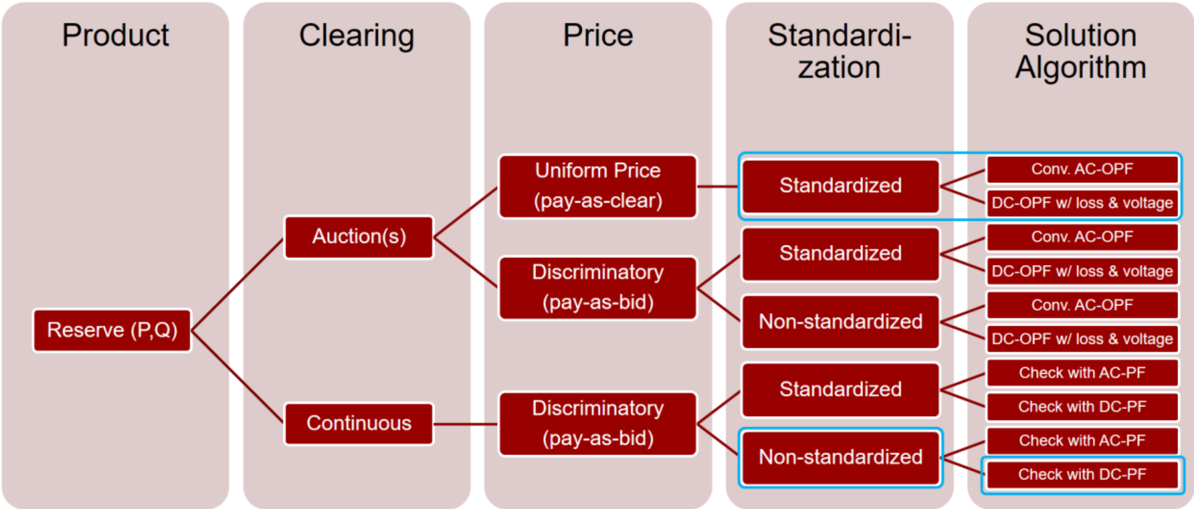

Figure 6: Market design choices for active power reserve distribution level flexibility market (DLFM)

4.3 Problem Formulation

In order to execute the algorithm, the following variables must be available to the FMO.

- **Network Data**: Network data includes network topology, line impedances, line power flow limits and voltage constraints.
- **Real and reactive power set points for the network:** For each time interval the real and reactive power demand and generation at each node is specified before running the algorithm from previous market positions, e.g. the wholesale day-ahead energy market.

4.3.1 Bids

The bids as placed as FlexRequest and FlexOffer:

- **Flexibility Request (FlexRequests)**: Both real and reactive power FlexRequests are accepted by the algorithm. They can either be conditional or unconditional (i.e. energy or power). Specifically, the components of a FlexRequest are (similar to **Error! Reference source not found.**):
  - Type – Conditional / Unconditional
  - Request Reserve type – Real or reactive power reserve
  - Direction – Up or Down
  - Price
  - Volume/ Quantity
  - Location- Bus/ node ID in the network
  - Time target: Specifies when the request should be activated
  - Time stamp: Specifies when the bid was submitted
- **Flexibility Offers (FlexOffers)**: Similar to FlexRequests, the FlexOffers can be submitted for either real or reactive power. Once the offer is submitted, the FMCT will look for a possible match with a FlexRequest. When a partial or complete match is found with any of the FlexRequests the offer is cleared. Specifically, the components of a FlexRequest are:
  - Request Reserve type – Real or reactive power reserve
  - Direction – Up or Down

- Price
- Volume/ Quantity
- Location- Bus/ node ID in the network
- Time target: Specifies when the request should be activated
- Time stamp: Specifies when the bid was submitted

The matching algorithm will look for a match once the bids for FlexRequests and FlexOffers are submitted. If a match is found, it is added to the list of cleared matches. Otherwise, it is added to the order book for requests or offers, respectively.

4.3.2 Shared Order Book

Incoming, non-matching bids are placed in a shared order book (SOB) until they are cleared with a matching bid. There is one SOB for Flex-Requests and one for Flex-Offers, and they contain all the details from the bids. They are sorted:

- By price first. For FlexRequests the bid with the highest price comes first and for FlexOffers, the bid with the lowest price comes first.
- By time stamp then. For two bids with the same price, the earliest comes first.

4.3.3 Matching Algorithm

A While matching a request the FlexOffers with the least price is considered first. For equally priced offers, the offer that arrived first has higher priority. When the FlexOffer price is less than or equal to the FlexRequest price for the same type of request, the matching algorithm runs a network check to look for possible voltage violations or line congestions. The matching algorithm has the following properties:

- **Automatic process:** It is triggered when a FlexRequest or FlexOffer is added or updated
- **Pay-as-bid pricing:** Each participant gets the price of the oldest bid of the two bids matching.
- **Best price:** A FlexRequest can only match with a FlexOffer with a price that is lower or equal.
- **First-come-first-served principle:** If they are two orders with the same price, the priority goes to the one that was submitted first.
- **Network check:** A network check is performed to ensure that the activation of the bids would not result in line congestions or voltage violation.
- **Partial execution:** If an offer/request is partially matched, the rest of the bid remains in the corresponding SOB. It is vital to allow partial matching of the bids. This way, the algorithm can match two bids right up to the point of line congestion or voltage violation.
- **Locational tagging:** The FlexOffer and FlexRequest can be located at different buses.

4.3.4 Network Check

LinDistFlow is a linearized approximation of the non-convex AC power flow [31]. In LindDistFlow, the line flow losses are neglected which ultimately allows to derive linear power flow equations. Unlike in DC power flow, the reactive power flow and voltage magnitude are part of the LinDistFlow. The LinDistFlow formulation is given in equations (4.1) to (4.3).

$$P_{i+1} = P_i - P_{L,i+1} \tag{4.1}$$

$$Q_{i+1} = Q_i - Q_{L,i+1} \tag{4.2}$$

$$V_{i+1}^2 = V_i^2 - 2(r_i P_i + x_i Q_i) \tag{4.3}$$

Where, P_i and Q_i are the net real and reactive power flow in branch i shown in Figure 7. $P_{L,i+1}$ and $Q_{L,i+1}$ indicates the real and reactive demand at node $i + 1$ and V_i is the voltage magnitude in node i.

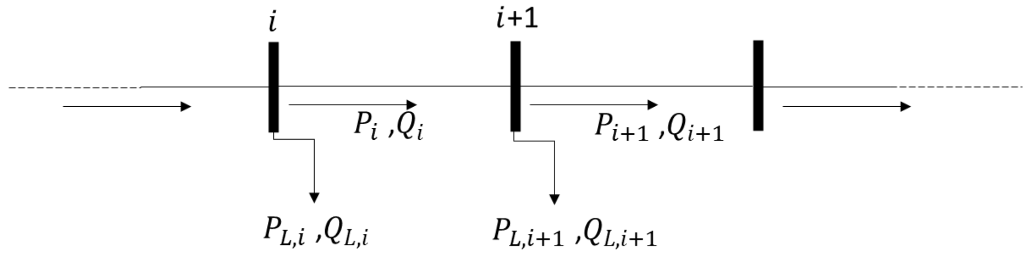

Figure 7: One line diagram of a radial network

When any network constraint violation is identified by the LinDistFlow network check algorithm, the quantity will be reduced by a small margin and the process will be repeated. Just as in Chapter 3, the network check algorithm will also look for any combination of accepted requests that could cause line flow congestion or voltage violation before accepting a match. This makes sure that the activation of all combinations of the accepted bid would not lead to a network issue. The order book's bids are re-evaluated once unconditional requests are matched, as they modify the power dispatch.

4.3.5 Multi-Period model

The matching algorithm is able to handle requests and offers for several market sessions at any point in time. Every new bid that is submitted contains a time target tag to which session it is submitted.

4.4 Proposed algorithmic solution

The algorithm used for matching an incoming bid is given in the figure below. In case of a match with an unconditional request, the matching algorithm runs again on the bids in the SOBs.

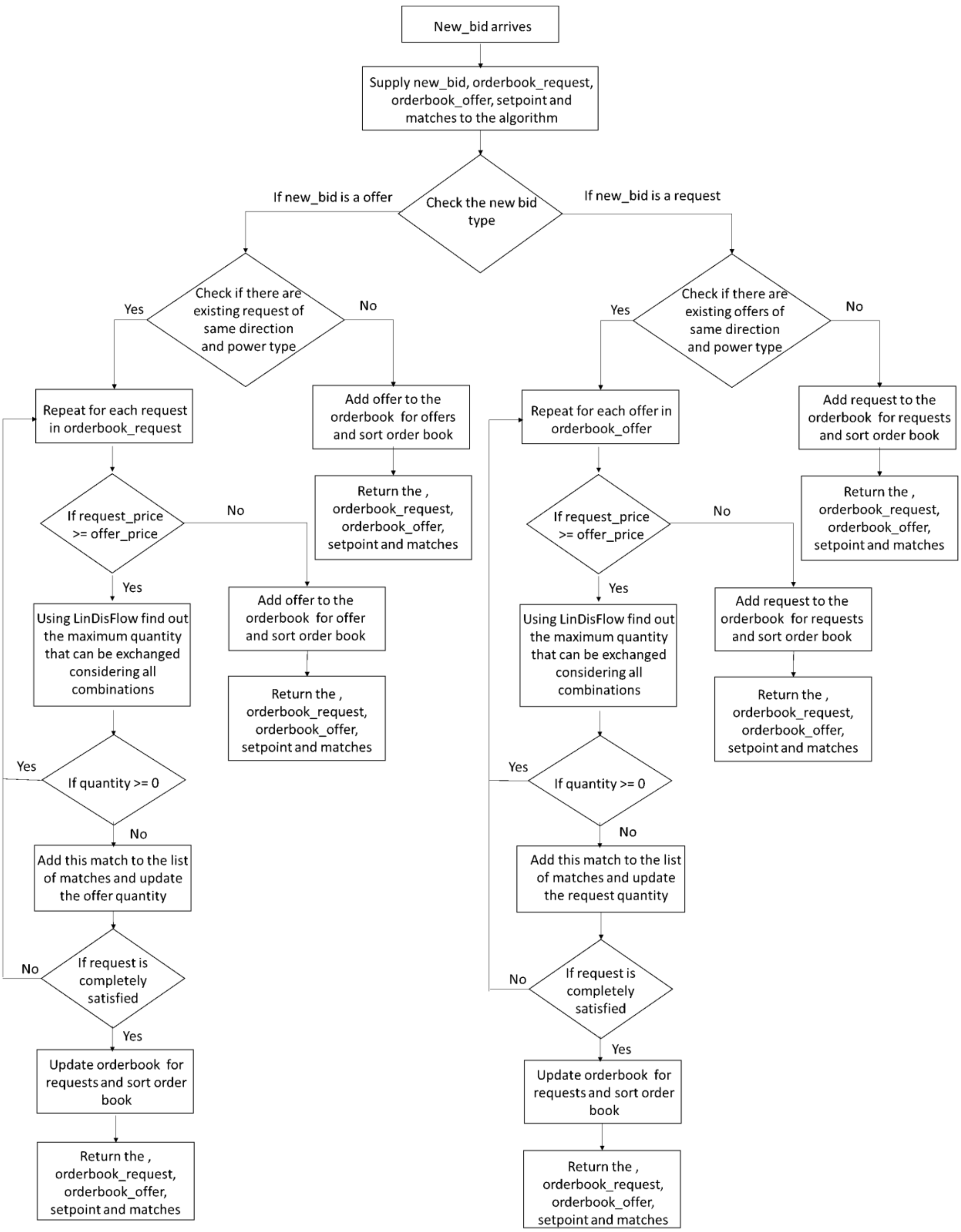

Figure 8: Heuristic approach for the Continuous DLFM Matching Algorithm for UCS 1.3

4.5 Simulation setup and performance evaluation results

4.5.1 Simulation setup and evaluation framework

The inputs needed by the market clearing algorithms are:

- Network Date: Network topology, line impedances, line power flow limits, voltage constraints, etc.
- Initial setpoint: Net power injections at each bus/node of the system that are determined in preceding markets
- Bids: New bid could be for a FlexRequest or a FlexOffer. The bid should include all the relevant details given in Section **Error! Reference source not found.**.

The outputs of the algorithm are:

- Accepted matches, which include the offer ID and request ID, which got matched, the quantity and matching price
- Social welfare, calculated as the difference between the utility of the accepted FlexRequests and the cost of the accepted FlexOffers (assuming all the participants submit their true utility/cost while bidding).
- Flexibility procurement cost, which corresponds to the cost of acquiring flexibility

The information about matches are gathered in a table. An example is shown in Table 9.

Table 9: Example of matches in UCS 1.3

Offer ID	Offer Bus	Request ID	Request Bus	Reserve type	Direction	Quantity	Matching Price	Time target
O1	Bus1	R3	Bus15	P	Up	0.01	39	T1
O2	Bus4	R6	Bus6	Q	Down	0.03	38	T2

4.5.2 Performance evaluation results

The algorithm was implemented in Python and the key performance indicators are given in Table 10.

Table 10: Key Performance Indicators for UCS 1.3

KPI	Description
Social Welfare	Sum of generation and demand welfare, given the utility of demand and cost function of generation.
Flexibility procurement cost	Cost of flexibility for the DSO
Curtailment	Total reduction in the number of FlexRequests matched due to line congestions
Cost reduction achieved	Difference in cost with implementing a reinforcement of the network instead of having flexibility markets

4.6 Next research steps for the M19-M26 period

Within M19-M26, we will elaborate on the UCS 1.3 work in order to deal in more depth with the following points:

- Implement an auction-based reserve market clearing algorithm using LinDistFlow
    - Study how to retrieve relevant market prices, since LMPs cannot be extracted in a continuous market.
    - Expand the model to include block bids.
- Complete the study on the continuous framework
    - Implement a more accurate, convex approximation of the AC-PF, e.g. the BranchFlow method as network check
- Include the calculation of all required KPIs
- Integrate algorithms in the FLEXGRID ATP

5 Possible DLFM integration with existing markets

Following up the advanced network-aware market clearing models and algorithms presented in the previous chapters for the proposed Distribution Level Flexibility Market (DLFM), we now discuss the possible DLFM integration with existing energy, reserve and near-real-time balancing markets. In section 2.3 of D5.1 [5], we have already undertaken an extensive review about all possible TSO-DSO coordination schemes that have been proposed so far in the international literature and in other related EU H2020 projects. Moreover, in Section 2.4 of D5.1 [5], we have described three main DLFM architectures together with their advantages and disadvantages. In this chapter, we proceed with the mathematical formulation, the algorithmic solution and initial performance evaluation of our proposed DLFM being integrated in today's energy markets.

5.1 Summary of the proposed Distribution Level Flexibility Market (DLFM) Architectures

The goal of FLEXGRID is to facilitate energy stakeholders to participate in electricity markets in an efficient, automated and optimal way. To do so, the FLEXGRID proposes the evolution of ***holistic energy market architectures***. With the term ***"holistic"***, we mean that FLEXGRID designs, develops and evaluates the performance (i.e. via system-level simulations at TRL 3) of energy market architectures, in which both energy and ancillary services are traded at both transmission and distribution network levels. One major requirement that has to be met towards this goal is the development of an advanced communication/interaction scheme between markets and networks, both at transmission and distribution network levels. This type of interaction between market and network domains as well as between MO and FMO and TSO and DSO is illustrated in the figure below.

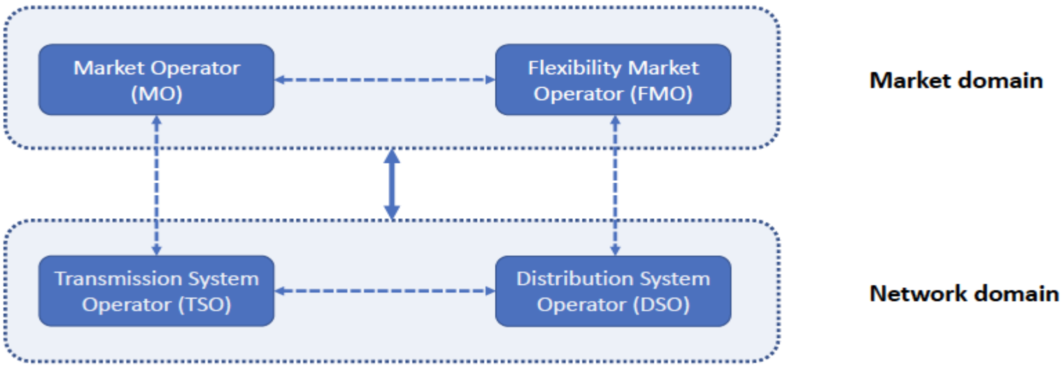

Figure 9: MO-FMO collaboration for better market efficiency outcomes and TSO-DSO collaboration for better network operation outcomes

FLEXGRID's premise is that TSO-DSO collaboration (i.e. network domain) can provide better network operation outcomes, while MO-FMO collaboration (i.e. market domain) can provide better market efficiency outcomes. Finally, the collaboration between network and market domains can ultimately lead to optimal and holistic energy market architectures.

Since there is no DLFM implemented in real business in EU area today, we take as a baseline the Nord Pool case that is operating in Nordic countries (and also NODES marketplace for decentralized flexibility trading - https://nodesmarket.com/) and we make the following assumptions:

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

Assuming that each market stakeholder can re-position itself via the balancing energy market, the intra-market might be neglected without affecting the structure of the proposed FLEXGRID energy market architectures. Thus, six markets take place, as shown below:

Table 11: Markets within FLEXGRID context

Market #1	The Market Operator (MO) operates the day-ahead energy market at the Transmission Network (TN) level.
Market #2	The TSO operates the day-ahead reserve market at the TN level.
Market #3	The Flexibility Market Operator (FMO) operates the day-ahead energy market at the Distribution Network (DN) level.
Market #4	The DSO operates the day-ahead reserve market at the DN level.
Market #5	The TSO operates the balancing energy market at the TN level.
Market #6	The DSO operates the balancing energy market at the DN level (only when DSO has a balancing responsibility for its DN operation).

The timing and the sequence of the markets for each x-DLFM architecture have been extensively described in Section 2.4 of FLEXGRID deliverable D5.1 and are briefly mentioned in the description of each x-DLFM architecture below. The interested reader may also look for more details about each x-DLFM architecture and the interaction among all involved stakeholders in Section 2 of D6.1[2].

5.1.1 Reactive DLFM architecture (R-DLFM)

The basic concept behind the development of the Reactive DLFM architecture is the capability of the distribution level (i.e. local) market to follow in an optimal way the decisions made by the wholesale market. For example, if we consider the traditional day-ahead energy market or reserve market, in the Reactive DLFM architecture, the local market succeeds the transmission level market.

[2] D6.1 will be publicly available in April 2021 here: https://flexgrid-project.eu/deliverables.html

In the baseline scenario, the R-DLFM architecture is characterized by the following market sequence: Market #1 → #2 → #3 → #4 → #5 → #6. It is assumed that the MO runs the day-ahead energy market (#1) as usual. Subsequently, given the MO dispatch schedules, the TSO operates the day-ahead reserve market at the transmission level (#2). Then, it is the turn of FMO to clear the local day-ahead energy market (#3) taking into consideration the particularities and the constraints of the distribution network, and so this is a DN-aware market clearing process. After that, a day-ahead reserve market (#4) at the local level might be needed, assuming that its operation resembles the corresponding market on transmission level. Then, the TSO operates the balancing energy market at the TN level (#5), and finally, if the DSO has a balancing responsibility of its network, a balancing energy market at the DN level (#6) should take place run by the DSO.

Of course, there might be some variants of the above-mentioned market sequence. For instance, in the occasion where only energy products are traded, i.e. the reserve provision is ignored, reserve markets both at transmission (#2) and distribution (#4) networks could be excluded. However, this might cause difficulties while the TSO and DSO should leverage their own flexibility or purchase flexibility to utilize it as reserves. Moreover, if the DSO doesn't have balancing responsibility for its network, then market (#6) is eliminated. In the case where the local flexibility assets bid only their capacity, the FMO part could be ignored and market #3 is excluded.

Overall, the R-DLFM architecture is compatible with the existing markets, as the wholesale market is not directly influenced. Indeed, as mentioned previously, the DN markets take place after the TN ones. Even though a loosely-coupled communication/coordination takes place between MO/TSO and FMO/DSO, the integration of distribution constraints into the market is indispensable to confront local congestion, local balancing and voltage control issues, especially in high RES penetration settings at the DN level. The FMO-DSO interaction issue is confronted by NODES platform via introducing a hierarchical structure of DN location areas, in which specific FlexAssets that are registered in the platform reside. Thus, when DSO makes a FlexRequest for a local congestion problem that occurs in DN location area 'X', then only FlexAssets that reside in DN location area 'X' are eligible to participate. When the DN-level problem concerns the whole DN, then all registered FlexAssets are eligible to participate. We also follow this architectural solution in the FLEXGRID Automated Trading Platform (ATP) that we develop in WP6 (see also Chapter 6 for more details).

Looking at the big picture, the R-DLFM is basically a leader-follower setup, since the distribution level markets always follow the decisions made at the transmission level markets, and therefore the social welfare is expected to be sub-optimal. This derives mainly from the inability of this architecture to pool together energy resources that are connected at different networks (TN and DN). In FLEXGRID, we also study a co-optimized approach to deal with this problem, which is the I-DLFM architecture that is presented below.

5.1.2 Proactive DLFM architecture (P-DLFM)

Contrary to the Reactive DLFM architecture, the P-DLFM architecture is developed to clear the distribution network (DN) level markets before the transmission level markets. As in the case of R-DLFM, the P-DLFM might include the day-ahead energy market, the day-ahead reserve market and the balancing energy market that take place at the distribution level, followed by the transmission level ones. This proactive (or else in advance) operation of the distribution level markets acts essentially as a feasibility check for the DN in order to handle possible infeasible transmission level dispatch and secure the feasible dispatch of assets connected to the distribution network.

Since in this case, the distribution level market precedes, the P-DLFM architecture is characterized by the following market sequence: Market #3 → #4 → #1 → #2 → #6 → #5. At first, the FMO runs the day-ahead energy market (#3) and after that, the DSO operates the day-ahead reserve market at the DN level (#4). Given the results from (#3) and (#4), the usual day-ahead energy (#1) and reserve (#2) markets take place. Finally, a proactive clearing of the balancing energy market on DN level (#6) might be needed, run by the DSO, before the balancing market operated by the TSO (#5).

The development of the P-DLFM architecture stems from the need to exploit the potential of the distribution network more dynamically. Nowadays, all that is done is that a rather static pre-qualification process takes places by the DSO at the distribution network level, however, in this way the markets #3, #4 and #6 are ignored, leading finally to sub-optimal results. So, the P-DLFM proposes a dynamic pre-qualification process and as a result, better results can be achieved mainly in high RES penetration scenarios at the DN. It is the aim of FLEXGRID research to provide numerical and comparative simulation results taking into account future high RES penetration scenarios in order to provide arguments for changing the current market architecture design and respective regulatory framework.

By implementing P-DLFM, the DN constraints are taken into account, thus possible voltage and congestion issues are solved proactively and consequently in a more economical way. An assumption that is made is that the residual bids (on DN level) can be forwarded to wholesale market leading to higher revenues for flexibility assets connected at the DN level. However, the latter could be a disadvantage for the TSO, because it could face higher re-dispatch costs due to the lack of cheap resources from the DN side, given that the DSO has already used the cheapest ones. Finally, social welfare might be much worse than the optimal and depends on how conservative (or not) is the proactive DN-level market clearing process. In this case, there may be room for strategic bidding (or else "inc-dec" gaming[3]), so in FLEXGRID, we also study on advanced market clearing schemes that incentivize truthful bidding by the flexibility suppliers (see more details in section 3.6 of D5.1).

5.1.3 Interactive DLFM architecture (I-DLFM)

In this architecture, the dispatch schedules for both TN and DN levels derive from an iterative process that occurs between MO-FMO and between TSO-DSO. This procedure converges to the optimal dispatch schedule and therefore to the optimal social welfare. Assuming that at both TN- and DN-level day-ahead energy, day-ahead reserve and balancing markets take place, then there should be three MO-FMO or TSO-DSO interactions, one for each type of market. In particular, the first interaction concerns MO-FMO coordination for the day-ahead energy market (markets #1 and #3), the second is about TSO-DSO cooperation for the

[3] https://nodesmarket.com/fear-of-gaming-should-not-be-a-barrier-for-market-based-redispatch-in-the-distribution-grid/

operation of the TN and DN reserve markets respectively (markets #2 and #4), while the last interaction deals with the near-real-time balancing markets (#5 and #6).

Because of the fact that I-DLFM achieves optimal social welfare, in the next section, the I-DLFM is described extensively, and particularly the implementation of this iterative process for the day-ahead energy market. As the discussion will be concentrated around the day-ahead energy market, the proposed market architecture will be called Iterative Distribution Level Energy Market (I-DLEM) and the FMO will be called Local Market Operator (LMO). Within this deliverable, we selected to present the mathematical model for the most complex market architecture (i.e. I-DLEM), which are also valid for R-DLFM and P-DLFM variants, and present initial simulation results. Within the subsequent deliverable D5.3, extensive comparison results will be provided for all above-mentioned x-DLFM architectures.

5.2 Introduction to I-DLEM idea, related work & FLEXGRID contributions

The increasing RES penetration and the flexibility provisioning pose new challenges to the power sector, therefore new approaches should be engineered to face such issues. Common problems that are expected to happen are local congestion and voltage instability at the distribution networks. A solution -that could cope up with these difficulties- is the network reinforcements, however, they should be studied carefully to avoid high expenditure. Besides, until now, the day-ahead energy market clearing does not take into account distribution network topology and constraints. As a result, our work is oriented to offer solutions on the above-mentioned issues. In fact, the I-DLEM architecture can take into consideration DN constraints and manage the RES penetration ensuring a feasible and optimal TN and DN schedule.

In the international literature, similar ideas can be found. Indicatively, in [32], a master (TSO) – slave (DSO) approach is proposed and an iterative process takes place to reach convergence. The stopping criterion stems from the voltage deviation at the boundary node. However, no network constraints are considered. In [33], the authors propose an economic dispatch to run on TSO and DSO level, where the operators interact with the boundary TLMP. Again, no network constraints are taken into account. Authors in [34] recommend a master-slave TSO-DSO cooperation using AC-OPF. The main interest of this paper is the satisfaction of constraints in the boundaries (i.e. coupling points) between TSO and DSO areas. Constraints of TSO and DSO are also taken into consideration. In [33], the authors perform economic dispatch on TSO and DSO level and iteratively obtain the TLMP on boundary node. In fact, a Coordinated Economic Dispatch is recommended.

The proposed I-DLEM provides the following novel contributions:

- The integration of distribution network constraints and topology into the market clearing process. The linearized DistFlow model is followed for the modelling of the DN.
- The achievement of maximum market efficiency through a joint market of both transmission (TN) and distribution (DN) level assets.
- The achievement of scalability through optimization theory. Specifically, a Dantzig-Wolfe decomposition is implemented to find the same solutions as in a centralized day-ahead energy market architecture, in which all small-scale DERs that reside at the

DN level could directly participate in the day-ahead energy market operated by a central MO entity. In other words, we achieve the same optimal results, but with much less computation time, which is a major pre-requisite for a market clearing process that takes place in a real-life business context.

- The efficient exploitation of flexibility assets through a multi-period market clearing process.
- Comparison of various x-DLFM architectures (i.e. no-DLFM, I-DLFM, P-DLFM, R-DLFM) via extensive system-level simulations and with respect to specific market and network efficiency related KPIs.

5.3 System model

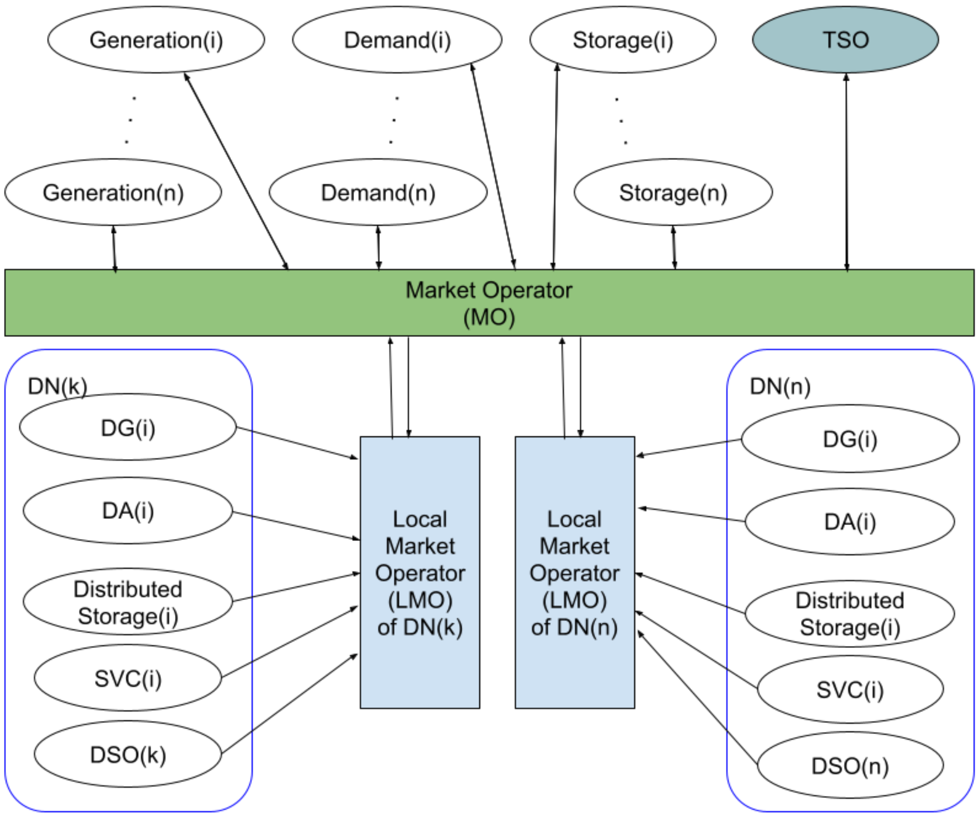

Figure 10: Market participants and their relation with MO and LMO

As already mentioned, within the I-DLEM architecture context, the clearing of the day-ahead energy market is the result of an iterative procedure between MO and LMO[4]. Therefore, MO (e.g. Nord Pool) and LMO (e.g. NODES) are the key market players. These stakeholders are responsible for the assets that reside at the TN and DN respectively. At the transmission network (TN) level, we model large energy producers (i.e. generation), large energy consumers (i.e. demand), large storage units and TSO's topology and constraints. Similarly, at the distribution network (DN) level, we model distributed generation (DG), demand

[4] We use the term "Local Market Operator - LMO" instead of FMO because a day-ahead energy market operation is considered, in which energy (not flexibility) is traded. The market clearing process followed by the LMO/FMO is extensively described in UCS 1.1 (cf. chapter 2). Please note that we also model the I-DLFM based on UCS 1.2-1.3 and the results will be reported in the subsequent D6.3 in Month 26.

aggregators (DA), distributed storage units, static var compensators (SVCs) and of course DSO's topology and constraints.

The transmission level assets manage their portfolio on their own, just following price signals, namely the Transmission Level Marginal Prices (TLMPs), published by the Market Operator (MO). At the DN, the situation is a bit different, due to the small scale of all the assets; the LMO is their representative in the wholesale market. Indeed, the LMO interacts with the MO only through the TLMPs published by the MO. Of course, it should be noted that the DN assets bid their cost/utility at their LMO and the respective DSO sends to the LMO the necessary information to take into account its topology and related DN constraints. We also make the assumption that the LMO has jurisdiction only at its respective DSO (cf. figure above).

The proposed market clearing process is executed in six steps. At **Step 1**, the MO declares the initial TLMPs at each transmission node (or else bidding zone)[5]. The initialization might be arbitrary without incurring any issues for the final convergence of the market clearing process. For instance, someone could choose the first TLMP values to be "zeros".

Then, at **Step 2**, two discrete processes take place. The first one (i.e. step 2a) corresponds to what is happening at the TN level, while the second one (i.e. step 2b) refers to what is happening at the DN level. As already mentioned, at the transmission network level, there are large producers, consumers, storage owners and the TSO, each one constituting a market participant at the TN-level day-ahead energy market operated by the MO. Each one of them would like to schedule its own portfolio in an optimal way, so all these different market players solve independently their own scheduling problem[6]. The only information needed, to generate their bidding decisions, is the corresponding TLMPs per transmission network node that are decided by the MO.

The second process of Step 2 (i.e. step 2b) concerns the local day-ahead energy market operated by the LMO. In this case, the LMO solves an optimization problem that includes the characteristics of all DN-connected assets, such as distributed generators, demand aggregators, static var compensators, while also taking into consideration DN constraints via information provided by the DSO. The LMO optimizes its portfolio using the offers/bids that DN-level assets have already submitted and the corresponding TLMP at the Point of Common Coupling (PCC).

Subsequently, at **Step 3** the dispatch schedules of TN-level assets and the dispatches of each LMO/DSO at the PCC with the TSO are communicated to the MO. The knowledge of the dispatches per TSO node is needed for the MO to take decisions for the next steps.

At **Step 4**, the MO checks if the set of last two TLMPs are the same (or close enough). If the check is true, the algorithm is terminated and the optimal solution is found, so the algorithm goes directly to Step 6. If the check is false, the algorithm continues with Step 5.

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[5] Our scheme is general enough and thus can be considered as a nodal pricing scheme. However, it is also compatible with the existing "bidding zone" pricing scheme that is adopted nowadays in the EU area.

[6] For more details about ESP's optimal bidding and scheduling problem, please see the FLEXGRID's advanced mathematical models and algorithmic solutions for ESPs in UCS 2.1 and UCS 2.3 in D4.1 (M12) and D4.2 (M18).

At **Step 5,** the update of TLMPs takes place via an optimization problem handling transmission network's power balance constraints and then the algorithm returns to Step 2. The MO executes the update using the dispatches known from Step 3.

Finally, at **Step** 6, the optimal solution is reached. The last calculated transmission, distribution dispatches and TLMPs determine the dispatches in the two networks.

As it is implied from the six steps above, the "intermediate" dispatches (i.e. iterative process between steps 2-5) of the I-DLEM are not actuated in reality. One could say that these iterations represent a virtual market clearing that eventually converges to the optimal solution, which is the dispatch result that the market participants both at TN and at DN should follow.

The following sequence diagram of the I-DLEM illustrates the proposed MO-LMO coordination scheme. The elongated box highlighted in purple color represents the I-DLEM clearing process that is proposed in this chapter. The elongated box highlighted in black color represents the existing day-ahead energy market clearing process, which is conducted by the MO. The first two blue boxes represent the optimal bidding process done by the ESPs (cf. UCS 2.3 analysis in D4.1 and D4.2 regarding "Maximize ESP's revenues" functionality), while the first orange box represents the optimal bidding process done by the aggregators (cf. UCS 4.3 analysis in D3.1 and D3.2 regarding "Create a FlexOffer" functionality).

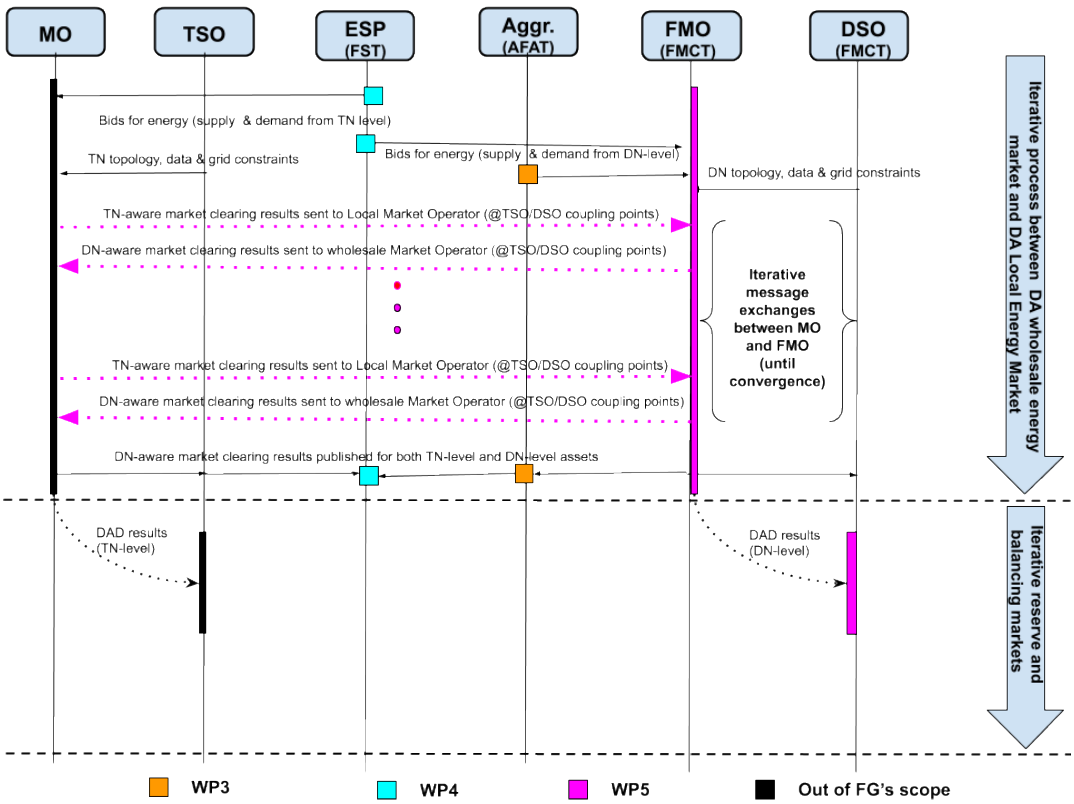

Figure 11: Interactive DLEM (iterative message exchanges between MO and FMO until convergence)

5.4 Mathematical model and problem formulation

In this section, the models of the various participants are presented. We will start describing the market players connected at the transmission network and then we will proceed with the description of DN-level assets.

5.4.1 Large Generators (supply side at TN level)

The large Generation Companies (GenCos) are profit seekers; they are focusing on minimizing their costs using their TN-level assets in an optimal way. The objective function minimizes the total generation cost, or else the difference between the production marginal cost $c_{i,t,b}$ and the (selling) price $\lambda_{i,t}$ for each quantity of energy traded. The Greek letter $\lambda_{i,t}$ indicates the TLMPs (prices). The set of producers is denoted by G, and it is assumed that each one owns b number of assets. Therefore, Equation (5.1) below is the objective function of the optimization problem that each GenCo $i \in G$ solves.

$$\min_{P^g_{i,t,b}} C_G = \sum_{t\in H}\sum_{b\in B}\{(c_{i,t,b} - \lambda_{i,t})P^g_{i,t,b}\} \tag{5.1}$$

$$P^{g,min}_{i,b} \le P^g_{i,t,b} \le P^{g,max}_{i,b} \quad \forall t \in H, b \in B \tag{5.2}$$

$$-RD_i \le \sum_{b\in B} P^g_{i,t,b} - \sum_{b\in B} P^g_{i,t-1,b} \le RU_i, \quad \forall\, t > 1 \tag{5.3}$$

$$-RD_i \le \sum_{b\in B} P^g_{i,t_0,b} - \sum_{b\in B} P^g_{i,t_0,b} \le RU_i, \quad t = 1 \tag{5.4}$$

Minimum and maximum limits on production Eq. (5.2) and ramping constraints in Eq. (5.3) and (5.4) are also taken into consideration.

5.4.2 Large Consumers (demand side at TN level)

On the demand side, the goal of each consumer is to maximize its utility, i.e. the load consumed multiplied by the difference between its marginal utility $U^d_{i,t,b}$ and the TLMP (Eq. (5.5)). The set of consumers is denoted by D, and it is assumed that each one owns b loads. Therefore, in each iteration, every consumer $i \in D$ solves the following optimization problem.

$$\min_{P^g_{i,t,b}} C_D = \sum_{t\in H}\sum_{b\in B}\{(\lambda_{i,t} - U^d_{i,t,b})P^d_{i,t,b}\} \tag{5.5}$$

$$P^{d,min}_{i,b} \le P^d_{i,t,b} \le P^{d,max}_{i,b} \quad \forall\, t \in H, b \in B \tag{5.6}$$

$$-R^{dn}_i \le \sum_{b\in B} P^d_{i,t,b} - \sum_{b\in B} P^d_{i,t-1,b} \le R^{up}_i, \quad \forall\, t > 1 \tag{5.7}$$

$$-R^{dn}_i \le \sum_{b\in B} P^d_{i,t_0,b} - \sum_{b\in B} P^d_{i,t_0,b} \le R^{up}_i, \ \ t = 1 \tag{5.8}$$

$$\sum_{t\in H}\sum_{b\in B} P^d_{i,t,b} \ge E^d_i \tag{5.9}$$

We consider minimum and maximum limits on consumption as shown in eq. (5.6), ramp up and down bounds (Eqs. (5.7)-(5.8)) and a minimum load that has to be always satisfied in eq. (5.9).

5.4.3 Storage Units connected at the transmission network

A storage unit can act either as generator or load. In generation mode (i.e. discharging), the storage units are paid at the relative TLMPs, whereas in load mode (i.e. charging), these units have to pay at the same TLMPs to the Market Operator for the amount of power they draw. In other words, in discharging mode the storage owners could gain profit (by selling energy), while in charging mode, they have to pay for the energy consumed for the charging. The State of Charge (SOC) is a function of charging and discharging and hence it is a constraint of the optimization problem. Each storage unit owner $i \in S$ solves the following optimization problem.

$$\min_{E_{i,t}, ch_{i,t}, dis_{i,t}} C_S = \sum_{t \in H} \left\{ \lambda_{i,t} \left(ch_{i,t} - dis_{i,t} \right) + MC_i^{ch} ch_{i,t} + MC_i^{dis} dis_{i,t} \right\} \quad (5.10)$$

$$0 \leq ch_{i,t} \leq \overline{ch_i} \quad \forall t \in H \quad (5.11)$$

$$0 \leq dis_{i,t} \leq \overline{dis_i} \quad \forall t \in H \quad (5.12)$$

$$E_{i,t} = E_{i,t-1} + \Delta \left(ch_{i,t} \eta^{ch} - dis_{i,t} / \eta^{dis} \right), \qquad \forall t > 1 \quad (5.13)$$

$$E_{i,t} = E_{i,o} + \Delta \left(ch_{i,t} \eta^{ch} - dis_{i,t} / \eta^{dis} \right), \qquad t = 1 \quad (5.14)$$

$$E_i^{min} \leq E_{i,t} \leq E_i^{max} \quad \forall t \in H \quad (5.15)$$

$$E_{i,T} = \gamma_i E_{i,o} \quad (5.16)$$

In the objective function (Eq. (5.10)), the Storage Unit owner minimizes its operating cost. Equations (5.11) and (5.12) limit the charging and discharging power respectively, while Eqs. (5.13) and (5.14) state the State of Charge (5.SOC) dynamic equation. Eq. (15) sets the lower and upper bounds of the storage unit's SOC at each timeslot. Last but not least, eq. (5.16) enforces that the SOC at the last time instant (T) will be a fraction of the initial SOC, so a minimum level of energy will be available at the beginning of the next scheduling horizon (i.e. next day). In other words, this is a restoration SOC constraint.

5.4.4 Transmission System Operator

The TSO, from its side, would like to minimize the transmission cost for delivering energy from one geographical region (TN node) to another. In fact, the TSO's optimization problem is formulated below. It should be noted that without loss of generality, load/generation forecast values are assumed to be input parameters to the TSO's cost minimization problem (i.e. deterministic solution approach). Using the common DC power flow model, the product $(\theta_{i,t}-\theta_{j,t})y_{i,j}$ is the power flow at line $(i,j)\in L$, while the subtraction $\lambda_{i,t}-\lambda_{j,t}$ shows the transmission cost from region i to region j (Eq. (5.17)).

$$\min_{\theta_{i,t}} C_{TSO}=\sum_{t\in H}\left\{\sum_{i,j\in L}(\lambda_{i,t}-\lambda_{j,t})(\theta_{i,t}-\theta_{j,t})\,y_{i,j}\right\} \tag{5.17}$$

$$-T_{i,j}^{max}\leq(\theta_{i,t}-\theta_{j,t})y_{i,j}\leq T_{i,j}^{max}\quad\forall(i,j)\in L,t\in H \tag{5.18}$$

$$-\pi\leq\theta_{i,t}\leq\pi\quad\forall i\in N,t\in H \tag{5.19}$$

In Eq. (5.17), $y_{i,j}$ is the admittance of the transmission line (i,j). Eq. (5.18) sets the lines' capacity limits, while via eq. (5.19), the nodal voltage angle is bounded.

5.4.5 Distributed Generators – DGs (supply side at DN level)

The limits of the distributed generators on active and reactive power are set based on equations (5.20) and (5.21). These bounds are related with physical constraints of DGs and weather conditions.

$$p_{i,t}^{DG,min}\leq p_{i,t}^{DG}\leq p_{i,t}^{DG,max}\;\forall i\in G^D,t\in H \tag{5.20}$$

$$\frac{p_{i,t}^{DG}}{\sqrt{\left(p_{i,t}^{DG}\right)^2+\left(q_{i,t}^{DG}\right)^2}}\geq PF_{i,min}\;\forall i\in G^D,t\in H \tag{5.21}$$

Eq. (5.21) can be transformed into a linear one as follows:

$$-\frac{p_{i,t}^{DG}*\sqrt{1-\left(PF_{i,min}\right)^2}}{PF_{i,min}}\leq q_{i,t}^{DG}\leq\frac{p_{i,t}^{DG}*\sqrt{1-\left(PF_{i,min}\right)^2}}{PF_{i,min}}\quad\forall i\in G^D,t\in H \tag{5.22}$$

since a minimum Power Factor (PF) could be assumed and considering that $p_{i,t}^{DG}$ and $PF_{i,min}$ are non-negative.

5.4.6 Distributed Energy Storage Systems (DESSs)

Equations (5.23) and (5.24) set the power limits of the charging and discharging mode of the distributed energy storage units (DESSs). In eq. (5.25), the SOC of each battery is shown, which depends on the SOC at the previous timeslot and of course on the charging and discharging power at the specific timeslot. The Greek letter η indicates the efficiency of charging and discharging modes. In Eq. (5.26), SOC limits are considered, while Eq. (5.27) ensures the restoration of SOC at the end of the day. The apparent power capacity of inverters is represented in Eq. (5.28). A positive value of $q_{i,t}^{DS}$ means the DESS generates reactive power. The equation (5.28) is replaced by a linear set of constraints using the inner polygon approximation, as in eq. (5.29):

$$0\leq p_{i,t}^{DS,dis}\leq p_i^{DS,dis,max}\;\forall i\in S^D,t\in H \tag{5.23}$$

$$0 \leq p_{i,t}^{DS,ch} \leq p_i^{DS,ch,max} \; \forall i \in S^D, t \in H \tag{5.24}$$

$$E_{i,t}^{DS} = E_{i,t-1}^{DS} + \eta_i^{DS,ch} * p_{i,t}^{DS,ch} - \left(1 / \eta_i^{DS,dis} \right) * p_{i,t}^{DS,dis} \; \forall i \in S^D, t \in H \tag{5.25}$$

$$E_i^{DS,min} \leq E_{i,t}^{DS} \leq E_i^{DS,max} \; \forall i \in S^D, t \in H \tag{5.26}$$

$$E_{i,T}^{DS} \geq E_{i,0}^{DS} \; \forall i \in S^D \tag{5.27}$$

$$\left(p_{i,t}^{DS,ch} - p_{i,t}^{DS,dis}\right)^2 + \left(q_{i,t}^{DS}\right)^2 \leq \left(S_i^{DS,max}\right)^2 \; \forall i \in S^D, t \in H \tag{5.28}$$

$$A_i \cdot \left(p_{i,t}^{DS,ch} - p_{i,t}^{DS,dis}\right) + B_i \cdot q_{i,t}^{DS} \leq \Gamma_i \; \forall i \in S^D, t \in H \tag{5.29}$$

where,

$$A_i = \begin{bmatrix} \sin\theta_0 - \sin\theta_1 \\ \sin\theta_1 - \sin\theta_2 \\ \vdots \\ \sin\theta_{M-2} - \sin\theta_{M-1} \end{bmatrix}$$

$$B_i = \begin{bmatrix} \cos\theta_1 - \cos\theta_0 \\ \cos\theta_2 - \cos\theta_1 \\ \vdots \\ \cos\theta_{M-1} - \cos\theta_{M-2} \end{bmatrix}$$

$$\Gamma_i = \overline{S_i^s} \cdot \begin{bmatrix} \cos\theta_1 \cdot \sin\theta_0 - \sin\theta_1 \cdot \cos\theta_0 \\ \cos\theta_2 \cdot \sin\theta_1 - \sin\theta_2 \cdot \cos\theta_1 \\ \vdots \\ \cos\theta_{M-1} \cdot \sin\theta_{M-2} - \sin\theta_{M-1} \cdot \cos\theta_{M-2} \end{bmatrix}$$

$$\theta = \frac{2\pi}{M}, \quad \theta_\kappa = k \cdot \theta, \quad k = 0, 1, \dots, M-1$$

with M indicating polygon's vertices number[7].

5.4.7 Demand Aggregators – DA (demand side at DN level)

The DAs can schedule their flexible demand consumers, and they are capable of accomplishing Demand Response. In eq. (5.30) and (5.31), limits on the active/reactive power of the loads are imposed:

$$p_{i,t}^{DA,min} \leq p_{i,t}^{DA} \leq p_{i,t}^{DA,max} \; \forall i \in D^{DA}, t \in H \tag{5.30}$$

$$0 \leq q_{i,t}^{DA} \leq p_{i,t}^{DA} * tan\left(acos(PF_i)\right) \; \forall i \in D^{DA}, t \in H \tag{5.31}$$

Both the active and reactive power related to the DA portfolio incur cost to the DA. Hence, the goal of the DAs is to achieve the lowest cost possible by trading their active and reactive power.

[7] It should be noted that a proper size of M should be selected in order to achieve a desired trade-off between efficiency and accuracy.

5.4.8 Static Var Compensators (SVCs)

The SVCs are reactive power elements that can either supply or absorb reactive power aiding to the voltage stability of the distribution network. Assuming that the SVCs operate in a continuous way, they are represented with eq. (5.32). If $q_{i,t}^{SVC}$ is positive, then the SVC offers reactive power to the grid.

$$q_i^{SVC,min} \leq q_{i,t}^{SVC} \leq q_i^{SVC,max} \quad \forall i \in D^{SVC}, t \in H \tag{5.32}$$

5.4.9 Distribution Network Model

The distribution network participates in the market as an aggregator of multiple and various distributed energy resources (DERs) that reside at the distribution grid, whose various models have been formulated above. Moreover, the topology and the constraints are included to represent more accurately the conditions that would hold at the grid based on the mathematical formulation below.

The distribution network model includes voltage bounds, lines' capacity limits, while the location of the various assets that reside within the network are integrated. The linearized DistFlow equations are used[8] as follows:

$$\sum_{k \in \Omega_p(n)} f_{nk,t}^p - \sum_{j \in \Omega_d(n)} f_{jn,t}^p = p_{i,t}^{DS,ch} + p_{i,t}^{DA} - p_{i,t}^{DG} - p_{i,t}^{DS,dis} \quad \forall n \in N^D, t \in H \tag{5.33}$$

$$\sum_{k \in \Omega_p(n)} f_{nk,t}^q - \sum_{j \in \Omega_d(n)} f_{jn,t}^q = q_{i,t}^{DA} - q_{i,t}^{DS} - q_{i,t}^{DG} - q_{i,t}^{SVC} \quad \forall n \in N^D, t \in H \tag{5.34}$$

$$U_{n,t} = U_{j,t} - 2 \cdot \left(r_{jn} \cdot f_{jn,t}^p + x_{jn} \cdot f_{jn,t}^q\right) \quad \forall n \in N^D, j \in \Omega_p(n), t \in H \tag{5.35}$$

$$U_n^{min} \leq U_{n,t} \leq U_n^{max} \quad \forall n \in N^D, t \in H \tag{5.36}$$

$$\left(f_{nk,t}^p\right)^2 + \left(f_{nk,t}^q\right)^2 \leq \left(S_{nk}^{f,max}\right)^2 \quad \forall nk \in B, t \in H \tag{5.37}$$

$$p_t^{sub} = \sum_{0k} f_{0k,t}^p \quad \forall t \in H \tag{5.38}$$

$$q_t^{sub} = \sum_{0k} f_{0k,t}^q \quad \forall t \in H \tag{5.39}$$

Eq. (5.33) indicates the active power balance, while Eq. (5.34) the reactive one. On the left side of the equations (5.33) – (5.34), there are the power flows, while on the right side the distributed production and consumption are included. The voltage drop on each DN bus is modeled via eq. (5.35) and the respective voltage limits that have to be satisfied are expressed in eq. (5.36). The non-linear equation (5.37) imposes the limits on the capacity of

[8] M. E. Baran, F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing", IEEE Trans. Power Delivery, vol. 4, no. 2, pp. 1401-1407, Apr. 1989.

the lines. As mentioned earlier, in the case of DESSs, eq. (5.37) can be replaced by a linear one using the inner polygon approximation.

5.4.10 Distribution Level Energy Market (DLEM)

In each iteration of the I-DLEM, the MO publishes updated nodal TLMPs (or else zonal TLMPs if we consider today's EU market). On the other hand, the LMO takes as input these hourly price signals[9] and its goal is to minimize the operational cost of the distribution network, meaning that is aiming at minimizing the cost of purchasing energy from the wholesale market and the costs related with the operation of DERs.

A difference between the DLEM and the wholesale market is the presence of reactive power. It has to be noted that even if the DERs absorb or offer reactive power, a cost is incurred. Thus, the objective function should include this particularity. A simple way to do so is by using the absolute values of $q_{i,t}^{DS}, q_{i,t}^{DG}, q_{i,t}^{SVC}$. The corresponding optimization problem of LMO is formulated as follows:

$$\begin{aligned}\min_{X^D} C_{DSO} = \sum_{\forall t \in H} \Bigg(& \lambda_t^{TSO,k} p_t^{sub} + \sum_{\forall i \in G^D} \left(c_{i,t}^{P,DG} p_{i,t}^{DG} + c_{i,t}^{Q,DG} \left| q_{i,t}^{DG} \right| \right) \\ & + \sum_{\forall i \in S^D} \left(c_{i,t}^{P,DS} \left(p_{i,t}^{DS,dis} + p_{i,t}^{DS,ch} \right) + c_{i,t}^{Q,DS} \left| q_{i,t}^{DS} \right| \right) \\ & + \sum_{\forall i \in D^{DA}} \left(c_{i,t}^{P,DA} p_{i,t}^{DA} + c_{i,t}^{Q,DA} q_{i,t}^{DA} \right) + \sum_{\forall i \in D^{SVC}} \left(c_{i,t}^{Q,SVC} \left| q_{i,t}^{SVC} \right| \right) \Bigg)\end{aligned} \tag{5.40}$$

subject to: (5.20), (5.22)-(5.27), (5.29)-(5.39)

The objective function (Eq. (5.40)) takes into account all the costs related with the operation of the distribution network. The term $\lambda_t^{TSO,k} p_t^{sub}$ indicates the cost of purchasing from or selling active power to the TN. The parameters $c_{i,t}^{P,DG}$ indicate production cost of active power from the DGs and $c_{i,t}^{Q,DG}$ is the cost related to the compensation of DGs for supplying or absorbing reactive power. In the DESSs case, there is a cost of active power for both charging and discharging $c_{i,t}^{P,DS}(p_{i,t}^{DS,dis} + p_{i,t}^{DS,ch})$ and a cost related to reactive power (consumed or offered), $c_{i,t}^{Q,DS}|q_{i,t}^{DS}|$. The price bids of the DA for active and reactive power are $c_{i,t}^{P,DA}$ and $c_{i,t}^{Q,DA}$ related with the respective quantities $p_{i,t}^{DA}$ and $q_{i,t}^{DA}$. The compensation of SVCs for supplying or absorbing reactive power is presented with the term $c_{i,t}^{Q,SVC}|q_{i,t}^{SVC}|$.

In order to linearize the absolute values, we add some auxiliary continuous variables $w_{i,t}$ and the following constraints:

$$w_{i,t}^{DG} \geq q_{i,t}^{DG} \qquad \forall i \in G^D, t \in H \tag{5.41}$$

[9] A vector of 24 hourly timeslots for the day-ahead energy market is assumed. We may also consider 15-minute time units (if real-life data will be available) in order to study whether there will be any difference in the need for flexibility.

$$w_{i,t}^{DG} \geq -q_{i,t}^{DG} \qquad \forall i \in G^D, t \in H \tag{5.42}$$

$$w_{i,t}^{DS} \geq q_{i,t}^{DS} \qquad \forall i \in S^D, t \in H \tag{5.43}$$

$$w_{i,t}^{DS} \geq -q_{i,t}^{DS} \qquad \forall i \in S^D, t \in H \tag{5.44}$$

$$w_{i,t}^{SVC} \geq q_{i,t}^{SVC} \qquad \forall i \in D^{SVC}, t \in H \tag{5.45}$$

$$w_{i,t}^{SVC} \geq -q_{i,t}^{SVC} \qquad \forall i \in D^{SVC}, t \in H \tag{5.46}$$

resulting to the following problem:

$$\begin{aligned} \min_{X^D} C_{DSO} = \sum_{\forall t \in H} \Bigg(& \lambda_t^{TSO,k} * p_t^{sub} + \sum_{\forall i \in G^D} \left(c_{i,t}^{P,DG} * p_{i,t}^{DG} + c_{i,t}^{Q,DG} * w_{i,t}^{DG} \right) \\ & + \sum_{\forall i \in S^D} \left(c_{i,t}^{P,DS} * (p_{i,t}^{DS,dis} + p_{i,t}^{DS,ch}) + c_{i,t}^{Q,DS} * w_{i,t}^{DS} \right) \\ & + \sum_{\forall i \in D^{DA}} \left(c_{i,t}^{P,DA} * p_{i,t}^{DA} + c_{i,t}^{Q,DA} * q_{i,t}^{DA} \right) + \sum_{\forall i \in D^{SVC}} \left(c_{i,t}^{Q,SVC} * w_{i,t}^{SVC} \right) \Bigg) \end{aligned} \tag{5.47}$$

subject to: (5.20), (5.22)-(5.27), (5.29) - (5.39) and (5.41)-(5.46).

5.5 Algorithmic solution (Dantzig-Wolfe decomposition method)

The concept of the I-DLEM (and obviously of the I-DLFM when flexibility units are traded), is the fragmentation of the market at the level of each market participant. In this way, each market stakeholder knowing its characteristics and particularities, is able to perform an optimal dispatch of its assets' portfolio. Certainly, due to the fact that the day-ahead energy market is cleared via the MO, the price signals sent by the MO are the lever to reach a market equilibrium that respects the power balance constraint at each TN node. Indeed, in the I-DLEM case, the TLMPs published by the MO actuate market players' reactions. In this section, the algorithmic process that defines the update of TLMPs decided by the MO is analyzed.

After receiving the dispatch decisions of the individual market stakeholders and their respective optimal costs, the MO updates the nodal TLPMs by solving the optimization problem that follows in each iteration v. This in fact is the implementation of Dantzig-Wolfe Decomposition algorithm [37].

$$\min_{u_k; k=1,\dots,v} \sum_{k=1}^{v} C^{(k)} u_k \tag{5.48}$$

subject to

$$C^{(k)} = C_G^{(k)} + C_D^{(k)} + C_S^{(k)} + C_{TSO}^{(k)} + C_{DSO}^{(k)} \qquad \forall k = 1,..,v \tag{5.49}$$

$$\sum_{k=1}^{v} u_k = 1 \tag{5.50}$$

$$\sum_{k=1}^{v} r_{i,t}^{(k)} u_k = 0: \quad \lambda_{i,t}; \quad \forall\, i \in N, t \in H \tag{5.51}$$

$$u_k \geq 0; \quad k = 1, \dots, v-1. \tag{5.52}$$

In the above optimization problem, the MO minimizes the entire network operational cost, which is defined as the sum of the individual costs optimally calculated by each market stakeholder (Eq. (5.49)). The optimization variables u_k represent the normalized weights of each intermediate solution to the final solution, the sum of which is ensured to be equal to 1 in Eq. (5.50).

In equation (5.51) the core of the TLMP update process is substantially hidden. The power balance mismatches at iteration k, in each TN node $i \in N$ and in each timeslot $t \in H$ are denoted by $r_{i,t}^{(k)}$. The mismatches $r_{i,t}^{(k)}$, $\forall\, i \in N, t \in H$, are calculated as follows:

$$r_{i,t}^{(k)} = P_{i,t}^{g^{(k)}} - P_{i,t}^{d^{(k)}} - ch_{i,t}^{(\mathrm{k})} + dis_{i,t}^{(k)} - p_t^{sub^{(k)}}$$

where $P_{i,t}^{g^{(k)}}$, $P_{i,t}^{d^{(k)}}$ are the corresponding on bus $i \in N$ generation and demand blocks (earlier written as $P_{i,t,b}^{g}, P_{i,t,b}^{d}$). The u_k weights those mismatches in order eq. (5.51) to hold. In essence, some iterations may lead to wrong solution and the $u_k$has the role to filter them out.
In Eq. (5.51) the weighted sum of the power balance mismatches is set to be zero – i.e. the demand should match the generation- and the respective dual variables, as known from optimization theory, are the TLMPs. Therefore, by solving the above optimization problem, we are able to obtain the desired TLMP updates. Those TLMPs will be used in the next iteration initiated by the MO, as the latter will provide the new TLMPs to all market stakeholders. Finally, Eq. (5.52) enforces weights u_k to be non-negative values.

The proposed I-DLEM architecture converges to the **same optimal solution** as in the case of a (hypothetical) **centralized market**, i.e. the market operator solves a large problem that jointly considers the costs and constraints of distribution and transmission assets and grids. With the proposed Dantzig-Wolfe algorithm, the convergence to the global optimal solution is guaranteed (since the various objective functions and the operating constraints are linear), however in a decomposed and consequently **scalable** way.

5.6 Simulation setup and initial performance evaluation results

In this section, some preliminary results are presented to prove the smooth operation of the market on I-DLEM architecture environment. The I-DLEM architecture is tested within a 14 bus Transmission System, with 2 GenCos having 5 and 4 assets respectively, 2 large consumers with 11 and 10 loads, 2 large storage units and 2 Distribution Networks. The characteristics of the DNs are shown in the following table that are connected with the TN (cf. Point of Common Coupling - PCC) at node 4 and 5 respectively. The data used, even if they might be simplistic in this initial version of performance evaluation, suffice to obtain some initial realistic results[10].

Table 12: Distribution Networks Characteristics

Distribution Network	#1	#2
DN Nodes	3	13
Distributed Generators	2	6
Distr. Storage Units	2	6
Demand Aggregators	2	9
SVCs	2	4

First, as shown in the next figure, the iterative procedure converges to a solution after several iterations. The lower and upper bounds shown below come from the Dantzig-Wolfe method that was explained earlier. The relatively great distance from the final social welfare value stems from the arbitrary choice of the initial TLMP values. Those TLMPs are corrected during the proposed iterative process. In the illustrated case, the initial TLMPs were "zeros" and were away from the final ones[11].

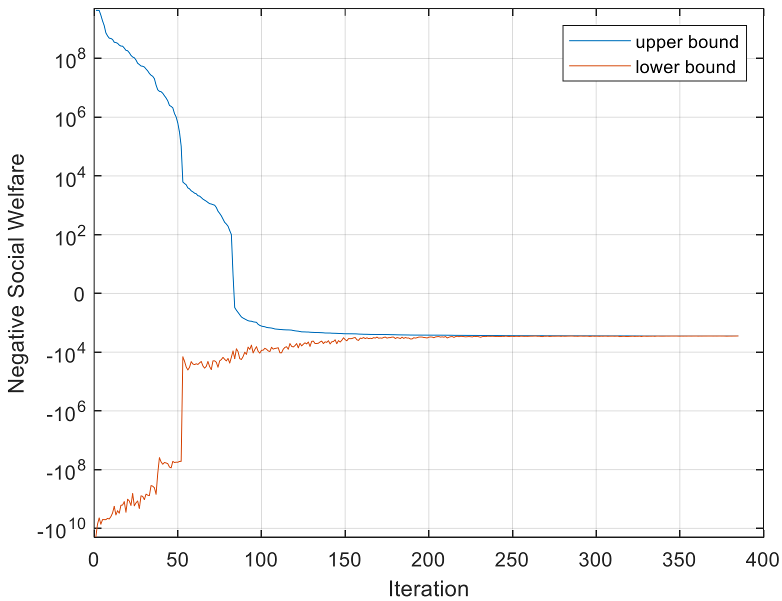

Figure 12: Convergence of I-DLEM

More specifically, the I-DLEM converges to the same Social Welfare (SW) as in the case of a centralized energy market. The next figure shows the social welfare that is achieved in three different cases. As expected, the I-DLEM architecture and the Centralized Market (Co-Optimization of TN and DN) achieve the same SW, which validates that our algorithm works well. In the next figure, the achieved SW of the No-DLFM architecture is also presented.

As was expected, the No-DLFM SW is greater than in the case of the I-DLEM. This difference is expected, as in the No-DLFM, the distribution network constraints are not taken into

[10] The data used to obtain the following results can be found at: https://github.com/FlexGrid/DLFM-integration

[11] It should be noted that a "better" starting value can be used (i.e. other than "zero") in order to improve the algorithm's performance (or else time to convergence).

consideration. This means that the assets that are connected at the DN could possibly operate up to their maximum values, while they are not restricted by the physical constraints of the distribution network. This freedom on their operation might be the cause of outages or curtailments due to the violation of voltage deviation limits as well as the congestion at the distribution lines. Given the fact that the Value of Lost Load (VoLL) is very high, we can infer that the real value of No-DLFM's social welfare will be much lower in real-life situations. We will include the VoLL in our model, use historical outage data and present updated results in the subsequent deliverable D5.3.

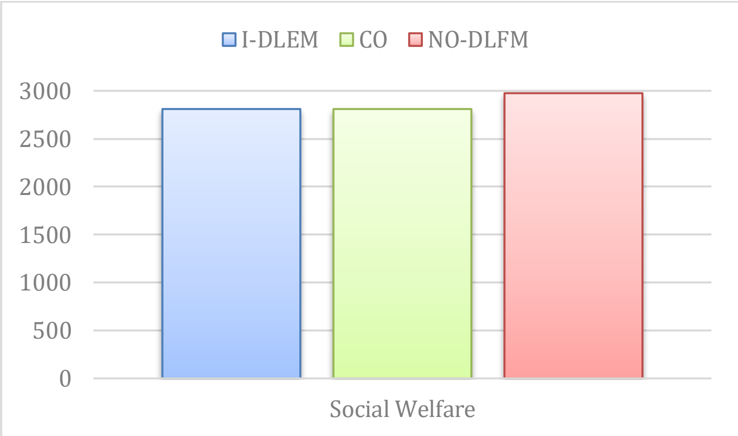

Figure 13: Social Welfare in I-DLEM, centralized optimization and NO-DLFM cases

Using the same simulation setup and data, i.e. generation, loads, distributed generation, storage, demand aggregation, etc., the I-DLEM is compared to No-DLFM. It is interesting to monitor the voltages and the capacity of lines of the distribution networks as in the No-DLFM, the corresponding constraints are neglected.

For a specific time instant, the satisfaction (✓) or the violation (✖) of voltage and line capacity limits are shown on the next tables. Moreover, the results of both cases are illustrated to show the deviations that exist.

The first comment of the results concerns the satisfaction of all network constraints in the case of I-DLEM. That of course is expected given that the I-DLEM formulation integrates the characteristics of the distribution network.

The voltage limits are explicitly set in the problem formulation and so an upper and a lower bound exist. However, the bounds of the flows are expressed via the linearization of eq. (37) and in fact, they are expressed with a set of inequalities depending on both active and reactive power flows at the same line. For instance, let us see the **P-flow 2** of DN#1 (cf. blue cells). The P-flow of I-DLEM is greater than in the No-DLFM, however, capacity violation happens only at the No-DLFM case. If we look closely, on I-DLEM, a reverse (minus sign) Q-flow at line 2 somehow cancels partially the P-flow 2 and thus the line is not overloaded.

Observing a bit more the results, in the No-DLFM, there are violations in both voltage and line capacity, as shown with the red crosses. In DN #1 case study, due to the topology of the connected assets, there is a need to transfer the energy from one place to another; so a congestion occurs in Flow 2. In node 3, the demand is greater than the generation and as a result, the voltage drops lower than the accepted limit. Of course, those issues do not exist in I-DLEM case.

Table 13: DN #1 results

DN #1	Line or Node	I-DLEM			NO-DLFM			Line Capacity / Voltage limits
		Results		Constraint satisfaction (✓) / violation(✗)	Results		Constraint satisfaction (✓) / violation(✗)	
Flows		P-Flows	Q-Flows		P-Flows	Q-Flows		
	1	0,0813	0,0685	✓	0,3000	0,0000	✓	Not explicit (see eq. 37)
	2	10,0813	-5,7050	✓	10,3000	0,0000	✗	
	3	1,3000	-0,6351	✓	1,3000	0,0000	✓	
Voltages	1	0,9564		✓	0,9924		✓	0.9025 <v <1.1025
	2	1,0146		✓	0,9650		✓	
	3	1,1025		✓	0,8950		✗	

Table 14: DN #2 results

DN #2	Line or Node	I-DLEM			NO-DLFM			Line Capacity / Voltage limits
		Results		Constraint satisfaction (✓ / violation(✗)	Results		Constraint satisfaction (✓ / violation(✗)	
		P-Flows	Q-Flows		P-Flows	Q-Flows		
Flows	1	0,1000	0,0084	✓	-1,3000	0,0000	✓	Not explicit (see eq. 37)
	2	0,6000	0,0084	✓	-0,8000	0,0000	✓	
	3	0,2000	0,0090	✓	-1,2000	0,0000	✓	
	4	-1,5000	0,2800	✓	-2,2000	0,0000	✓	
	5	-1,5000	0,2800	✓	-2,2000	0,0000	✓	
	6	1,8000	-0,2710	✓	1,1000	0,0000	✓	
	7	1,8000	-0,2710	✓	1,1000	0,0000	✓	
	8	-1,0000	-0,2710	✓	-1,7000	0,0000	✓	
	9	-1,5000	0,0000	✓	-2,2000	0,0000	✓	
	10	0,6000	0,0000	✓	0,6000	0,0000	✓	
	11	0,4000	-0,0006	✓	0,4000	0,0000	✓	
	12	-0,8000	0,0050	✓	-0,8000	0,0000	✓	
	13	0,3000	0,0000	✓	0,3000	0,0000	✓	
Voltages	1	0,9924		✓	1,0330		✓	0.9025 <v <1.1025
	2	0,9906		✓	1,0352		✓	
	3	0,9777		✓	1,0997		✓	
	4	1,0140		✓	1,2025		✗	
	5	1,1025		✓	1,4534		✗	
	6	0,9423		✓	1,0287		✓	
	7	0,9025		✓	0,9489		✓	
	8	1,0297		✓	1,0449		✓	

	9	1,0741	✓	1,1100	✗	
	10	1,0305	✓	1,0664	✓	
	11	0,9025	✓	0,9464	✓	
	12	1,1025	✓	1,1497	✗	
	13	1,0065	✓	1,0538	✓	

In DN #2 case study, in the No-DLFM case, no capacity violations happen due to the higher liquidity of production and consumption assets as well as the location that they are placed. However, due to mismatches of generation and demand at several nodes, voltage violations occur. This in fact is a separate research thread that is going to be analyzed in the subsequent deliverable D5.3.

For instance, several scenarios of various levels of flexibility penetration in the DN will be examined to solve local congestion and voltage problems. In this sense, a sensitivity analysis for FlexAssets' sizing and siting in the DN will be realized. Within the sensitivity analysis, we will be able to quantify the cost of the possible outages based on already known historical datasets that refer to distribution network level outages.

5.7 Next Steps

Within M19-M26, we will continue our work on testing and validating the performance of I-DLEM and I-DLFM architectures by simulating more network setups and case studies at TRL 3. Our main goal is to develop the various FLEXGRID x-DLFM architectures and compare it with the I-DLFM as follows:

- **No-DLFM architecture:** this is the baseline architecture that represents the current regulatory framework in which no DLFM actually exists in the EU area.
- **Reactive DLFM architecture:** DLFM follows day-ahead energy market (MO) and day-ahead reserve market (TSO)
- **Proactive DLFM architecture:** DLFM precedes day-ahead energy market (MO) and day-ahead reserve market (TSO)

In D6.3, we will report more performance evaluation results based on various test cases/scenarios and KPIs.

The envisaged analysis will include:

- several RES penetration level scenarios at DN
- distribution assets placed on different sites
- multiple small assets vs one large asset (with the same total capacity)
- several DN topologies
- comparison of flexibility liquidity scenarios at DN and
- extended comparison between DN-aware and DN-unaware market clearing

Indices for evaluating the operation might be the number of times a voltage violation or a local congestion takes place. Furthermore, the separate and total flexibility cost of TN and DN might be useful. Of course, as already used, the Social Welfare would have a primordial role on the examination of the different test cases.

Our objective, is also to use real data of networks and stakeholders to show the applicability of the proposed markets in a realistic manner. Such extended results will facilitate the implementation of the proposed markets or improve the current ones.

6 S/W integration in FMCT and FLEXGRID ATP

The main user of the FMCT is the Flexibility Market Operator (FMO), who clears a local energy or reserve market after (R-DLFM) the transmission level commitments have been cleared. This means that some of the local generators and loads may already have committed parts of their energy and/or reserve to the wholesale transmission level. The FMO runs a continuous pay-as-bid market, where FlexRequest from the DSO and FlexOffers from FSPs are continuously accepted and added to the orderbook. When the prices match, a network check is performed in order to ensure that no network constraint is violated. Without loss of generality and within FLEXGRID's context, we assume that the full network model of the DSO is known to the FMO, as well as the active and reactive power setpoints committed in the wholesale transmission level market. The aim of the FMO is to maximize social welfare by matching all bids that result in feasible power flows.

The novelty of the FLEXGRID's algorithmic approach is that the FMO clears the market continuously and under full consideration of network constraints, i.e., including line and transformer ratings, reactive power limits, and voltage bands. A second contribution is that this algorithm ensures that any combination of reserve activation is feasible for the network. Current approaches of reserve clearing do either (i) not consider the network at all, or (ii) only aim to find one single reserve combination per contingency that yield feasible power flows.

6.1 Summary of FMCT functionalities and related S/W development

The Flexibility Market Clearing Toolkit (FMCT) has been designed in a way that can be commercially exploitable as a standalone S/W toolkit, which can be integrated as a S/W "plug-in" in other larger S/W platforms developed by a FMO in the future. Within the FLEXGRID context, FMCT will be integrated in the FLEXGRID S/W platform (ATP) and its operation will be tested via extensive lab experimentations and pilot tests within WP6.

So far, in FLEXGRID, we have done the following work with respect to the FMCT:

- We have developed a first version of the FMCT functionalities. In other words, we have developed and tested the first version of the research algorithms that will be running at the FMCT's backend. The initial algorithms and research results are detailed in chapters 2-4 of the current document.
- FMCT's data modelling work has been started and is provided in D6.1[12] (M18).
- As part of WP8 business modeling work, we have identified the FMCT's Key Exploitable Results (KERs). More details are provided in D8.2 (M18).

From M19 onwards, we will continue the WP5 research and will start integrating the first version of the algorithmic solutions in the FMCT. Then, we will extensively test and validate our algorithms in FLEXGRID ATP at TRL 5. The progress of FMCT's development throughout the whole project's lifetime is as follows:

[12] https://flexgrid-project.eu/deliverables.html

- Within WP5, we conduct high-quality scientific research work by developing advanced mathematical models and algorithms beyond state-of-the-art and publish them in high-quality scientific journals and conferences (TRL 3).
- After the extensive testing and validation of the proposed algorithms at TRL 3, the next step is the coordination with WP6 for the integration of FMCT's frontend and backend services.
- The next step is the testing and validation of the FMCT algorithms via the use of FLEXGRID ATP at TRL 5 (WP6).
- Finally, we may conduct small-scale test with a real-life distribution network of bnNETZE (TRL 6).

6.2 FMCT's frontend services

The FMO user will be able to use a several services from the FLEXGRID ATP. The Graphical User Intefaces (GUIs) will be developed in WP6.

FMCT's frontend (GUI) will be comprised of three basic configuration tabs, namely:

- Selection of the DLFM area
- Selection of type of market clearing algorithm
- Selection of network model

By running a selected clearing algorithm, the FMO will be able to visualize the key outputs, including cleared volumes, prices, and social welfare. We distinguish two main operation modes for the FMO's GUI, namely: We distinguish two main operation modes for the FMO's GUI, namely:

- **Online operation**: The FMO user has the initiative. It accepts FlexOffers and FlexRequests and matches them in a continuous fashion whenever a new bid arrives. These cleared bids should also be made visible for the FSP user (i.e. FlexSeller) and DSO user (i.e. FlexBuyer).
- **Offline operation**: The FMO user runs various "what-if" simulation scenarios to identify how it can achieve maximum expected social welfare. Only the FMO user will be able to visualize the results.

The ESP/FSP user and DSO user will also be able to view some of the information. As a result of UCS 1.1, 1.2, and 1.3, three different screens will be developed. Depending on the type of user, the presented data in some of them will be slightly different, see Table 15.

Table 15: FMCT Frontend

	FMO user	ESP user	DSO user
Flexibility market clearing Optimizations			
Flexibility market clearing Optimization configuration			
Flexibility market clearing Optimization results			

6.3 AFAT's backend services and integration in FLEXGRID ATP

The following tables summarize the input parameters for the algorithm to run in the FMCT backend and output parameters for the results to be visualized in FMO's GUI (i.e. FMCT frontend) respectively.

6.3.1 Input Parameters

The input parameters to UCS 1.1, 1.2, and 1.3 are summarized below.

Input parameters	**Description**	**FMO GUI in ATP**	**Central FG database**
DLFM area		Select FMO/DSO data per country (drop down menu with a few countries, e.g. Germany, Norway, Croatia)	The ATP-DB API will fetch the FMO user's inputs to the DB. The DB-FMCT API will fetch the selected time interval and selected markets from the central DB to the FMCT.
Market time horizon	The default is 24 hours in 1h time resolution	Select time interval 'X' date to 'Y' date (cf. calendar)	
Energy balance forecast	Forecast active and reactive load and generation at each node, representing the external, previously cleared and accepted bids from all ESP users including the volume and node (assumed as known in WP5)	active and reactive power setpoints per node and timestep	
Distribution network data	Lines with impedances, line current limits, bus voltage limits, bus voltage phase angle limits.	In the form of a distribution network ID: Lines with impedances, line current limits, bus voltage limits, bus voltage phase angle limits.	
DLEM market bids from all ESPs and DSO	Includes attributes -Nature: FlexOffer (from ESP) or FlexRequest (from DSO) -quantity -direction (up/down) -location ID -timestamp -time target -price (€/MWh/h)	Sort by price, location, (maybe volume)	
DLFM market bids from all FSPs and DSO	Includes attributes -Nature: FlexOffer (from FSP) or FlexRequest (from DSO) -Type: (for a FlexRequest): Conditional or Unconditional -quantity -direction (up/down) -type: active/reactive -location ID	Sort by price, location, (maybe volume)	

	-timestamp -time target -price (€/MWh/h)		
Shared Order Book[13]	contains all previously placed bids (DLEM/DLFM market FlexRequests and FlexOffers) that are not yet matched		
Accepted Requests[14]	contains all previously accepted bids (DLFM market FlexRequests and FlexOffers) that are matched		
Type of market clearing algorithm	Two algorithms are available - continuous (pay-as-bid) - auction (pay-as-clear)	Select from dropdown menu - continuous (pay-as-bid) - auction (pay-as-clear)	Type of market clearing algorithm
Type of optimal power flow	Different algorithms are available, so far -DC-(O)PF without losses and voltages -DC-(O)PF with approximations of losses and voltages -LinDIstFlow-(O)PF -BranchFlow-(O)PF	Select from dropdown menu	Type of optimal power flow
(*Optional:* Active power exchange from TSO)[15]		Default value is 0	The ATP-FMCT API will fetch the required data from the TSO's inputs to FMCT.
(*Optional:* Reactive power exchange from TSO)[16]		Default value is 0	
(*Optional:* Excess active energy FlexOffers not cleared in the wholesale market, available for DLEM)[17]		Default value is 0	
(*Optional:* Excess active power FlexOffers not cleared in the FM, available for DLFM)[18]		Default value is 0	

[13] For continuous clearing
[14] For continuous clearing
[15] in the case of R-DLFM
[16] in the case of R-DLFM
[17] in the case of R-DLFM
[18] in the case of R-DLFM

6.3.2 Output Parameters from the algorithm's results to be visualized in FMO GUI (ATP):

The output parameters from UCS 1.1, 1.2, and 1.3 are summarized below.

Output parameters	Description	FMO GUI in ATP	Central FG database
dLMP for all distribution nodes and time steps[19]	Distribution Locational Marginal Price for energy at each node and each time step (€/MWh/h)	The ESP and DSO users should also be able to visualize this on their own GUIs. should be accessible as both: -raw data files, e.g. tables -visualization, for instance a heat map, where you can zoom in and out. If there are too many nodes, then aggregated values per "grid node"/per pre-defined zone can be visualized instead.	
pLMP for all distribution nodes[20]	Distribution Locational Marginal Price for active power reserve at each node and each time step (€/MW/h)		
qLMP for all distribution nodes[21]	Distribution Locational Marginal Price for reactive power reserve at each node and each time step (€/MVar/h)		
Cleared volume of energy for all distribution nodes and time steps	Volume of active power generation and load, i.e., energy per time step at each node and each time step	The ESP and DSO users should also be able to visualize this on their own GUIs. should be accessible as raw data files, e.g. tables Probably visualization is not needed	The FMCT-ATP API will fetch the results from the FMCT to ATP. The FMCT-DB API will store the same results to the central DB.
Cleared active reserve volume for all distribution nodes and time steps	Volume of active power reserve at each node and each time step		
Cleared reactive reserve volume for all distribution nodes and time steps	Volume of reactive power reserve at each node and each time step		
Shared Order Book[22]	contains all previously placed bids (DLEM/DLFM market FlexRequests and FlexOffers) that are not yet matched	The DSO and ESP and FSP user should also be able to visualize this on their own GUIs. should be accessible as raw data files, e.g. tables	
Accepted Requests[23]	contains all previously accepted bids (DLFM market	The DSO user should also be able to visualize this on their own GUIs.	

[19] for DLEM auction, UCS 1.1

[20] for DLFM auction, UCS 1.2 and UCS 1.3

[21] for DLFM auction, UCS 1.3

[22] For continuous clearing

[23] For continuous clearing

	FlexRequests and FlexOffers) that are matched	should be accessible as raw data files, e.g. tables	
Voltage magnitudes at all distribution nodes and time steps[24]	Voltage magnitude in p.u. at each node and at each time step	The DSO user should also be able to visualize this on their own GUIs. should be accessible as both: -raw data files, e.g. tables -visualization, for instance a heat map, where you can zoom in and out. If there are too many nodes, then aggregated values per “grid node”/per pre-defined zone can be visualized instead.	
Voltage magnitude limits at all distribution nodes	This is part of the input “Distribution network data”		
Power flows over all distribution lines and time steps[25]	Power flow in MW/h over each line at each time step. Lines connect nodes, and each node is connected to at least one line.	The DSO user should also be able to visualize this on their own GUIs. should be accessible as both: -raw data files, e.g. tables -visualization, for instance a heat map, where you can zoom in and out. If there are too many nodes, then aggregated values per “grid node”/per pre-defined zone can be visualized instead.	
Power flow limits over all distribution lines	This is part of the input “Distribution network data”		
(*Optional:* Active power exchange with TSO)[26]	a single number	The DSO user should also be able to visualize this on their own GUIs. should be accessible as both: -raw data files, e.g. tables -visualization, for instance a single number on the map at the interface node of DSO and TSO grid	
(*Optional:* Reactive power exchange with TSO)[27]	a single number		
(*Optional:* Excess energy FlexOffers not cleared in the DLEM, available for FM)[28]	A share of the FlexOffers that was not cleared in the FMCT and remains	The ESP and DSO users should also be able to access this. should be accessible as only raw data files, e.g. tables, visualization is probably not needed.	
(*Optional:* Excess active power reserve FlexOffers not cleared in the DLFM, available for FM)[29]	A share of the FlexOffers that was not cleared in the FMCT and remains		

[24] For DLEM UCS 1.1
[25] For DLEM UCS 1.1
[26] for P-DLEM/P-DLFM
[27] for P-DLEM/P-DLFM
[28] for P-DLEM
[29] for P-DLFM

(*Optional:* Excess reactive power reserve FlexOffers not cleared in the DLFM, available for FM)[30]	A share of the FlexOffers that was not cleared in the FMCT and remains		
Social Welfare	A single number per day or month	This is a more research related parameter. It is sufficient to extract it as raw raw data files, e.g. tables	
Flexibility Procurement cost	A single number per day or month		

[30] for P-DLFM

7 Conclusions and next steps

To the best of our knowledge, we propose for the first time a design of a *continuous* local flexibility market (DLFM) that explicitly considers network constraints. We discuss the general architecture of such a market, the structure of the FlexRequests, and elaborate on a number of design options for the inclusion of network constraints in the market clearing. In the early stages of local flexibility markets, where insufficient liquidity may hinder market development, continuous markets are expected to be the most suitable option. At the same time, in increasingly loaded distribution systems, including the network constraints in the market clearing ensures that every matched pair of bids will not violate operational limits, and would not require additional actions from the distribution system operators that result in additional costs.

In the following months, WP5 partners will progress the current research work on continuous clearing algorithms presented in this report and will provide the final research results in D5.3 in Month 26. Additionally, auction based market clearing algorithms will be presented in D5.3.

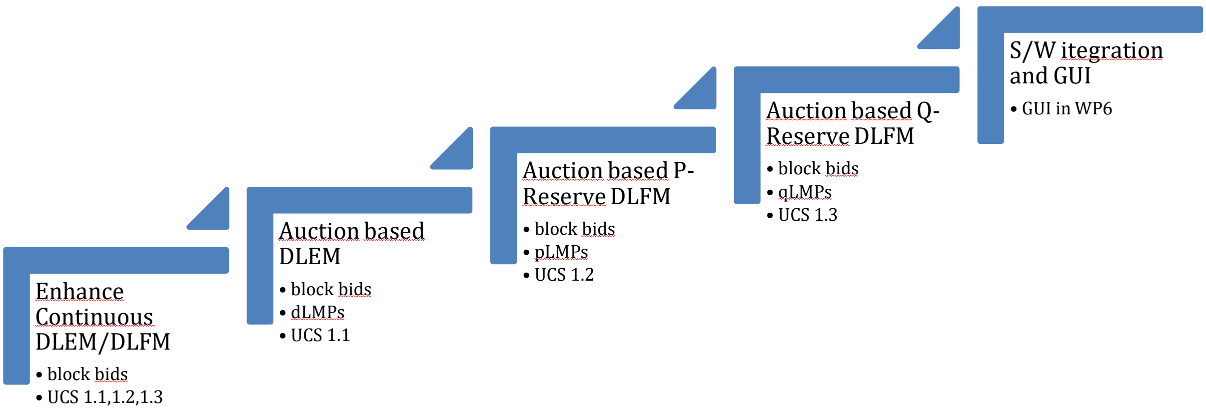

Figure 14: Next steps towards deliverable D5.3 in M26

Specifically, Figure 14 shows the next steps in more detail. The first step is to include block bids into the continuous clearing algorithms for all three use case scenarios; UCS 1.1, UCS 1.2, UCS 1.3. The second step is to develop an auction based network-aware DLEM clearing algorithm for UCS 1.1, which can include block bids and computes distribution level locational marginal prices (dLMPs). The third step is to develop an auction based network-aware DLFM clearing algorithm for UCS 1.2, which can include block bids and computes distribution level active power reserve LMPs (pLMPs). The fourth step is to develop an auction based network-aware DLFM clearing algorithm for UCS 1.3, which can include block bids and computes distribution level reactive power reserve LMPs (qLMPs). Throughout the next month leading up to M26, a close link with WP6 will ensure the S/W integration of the algorithms and GUI.

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