FPS Economy, S.M.E.s, Self-employed and Energy

ECOFLEX

D5.1 Report on Multi-Energy Flexibility Markets

With the support of the Energy Transition Fund

Version number and Date: Version 1, 17/03/2025

Author (s): Muhammad Andy Putratama

Abstract for dissemination (PU)

This document presents the concept of ECOFLEX ecosystem, which includes the interaction mechanisms between local flexibility provider (e.g., site), universal flexibility platform (UFP) and flexibility requesting parties (such as aggregator or balancing responsible parties). The document also presents a market scheme that can be organized thanks to the UFP. The presented market mechanism will allow flexibility valorization in energy communities by taking into consideration energy sharing scheme, while also mitigate potential grid problems at local level.

Contents

1. Introduction 3

2. ECOFLEX Ecosystem 4

    2.1 Overview 4

    2.2 Challenges 7

3. Two-Stage Local Flexibility Markets 8

    3.1 Definition 8

    3.2 Mathematical Model 9

        3.2.1 Grid model 9

        3.2.2 Energy storage model 10

        3.2.2 Energy Community Operation and Market models 11

4. Simulations and Results 15

5. Conclusion & Future Works 19

References 20

1. Introduction

The energy sector is changing at a tremendous speed, driven by climate-neutral goals, increased targets linked to the build-out of renewable energy sources, and the electrification of society as well as concerns related to energy security and affordability. Currently, distribution power systems are now being integrated with distributed energy resources (DERs) and on a major transition into a more active role with a capability of bidirectional transportation. This evolution allows consumers to deploy their own DERs, such as photovoltaic systems (PV), energy storage systems (ESS), heat pump, and electric vehicles (EV). Hence, consumers are now becoming prosumers, which is capable not only to consume, but also to produce energy and provide flexibility to the power grid.

Although the widespread adoption of DERs can bring many benefits for distribution power systems, it also imposes numerous operational challenges (e.g., reverse power flows, congestion and voltage problems [1]), to distribution system operators (DSOs). This mainly due to the legacy distribution grids that were designed with “fit and forget” approach, which implies that all the possible technical issues are resolved in the planning stage, makes use of very few monitoring tools and expect the grid infrastructure to be capable of operating under the worst-case scenario, using the assumption of unidirectional power flow, which is not valid anymore with the rising presence of DERs. These operational challenges will occur when a distribution grid exceed its hosting capacity (HC) limit.

Therefore, the aforementioned challenges highlight the need of flexibility and operational changes in distribution power systems, particularly in low-voltage (LV) grids. Flexibility is defined as a capacity the capability of an entity (e.g., prosumer) to modify its generation and/or consumption (on an individual or aggregated level) to meet demands of system operators or different marketplaces [2]. Currently, there are growing research works on prosumers’ flexibility valorisation in energy communities (ECs). Typically, prosumers can valorise their flexibility in the existing markets through a third-party entity (i.e., aggregator) who acts as an intermediary [3], [4]. To do this, a community can organize a so-called local energy market (LEM) to facilitate the energy and flexibility exchange among prosumers. Yet, one of the limitations of existing LEM mechanisms is the incapability of the market clearance to mitigate potential local grid problems.

This deliverable is the summarization of the result of task 5.1 of the ECOFLEX project. One of the main results of the task is the ECOFLEX ecosystem that allow users (e.g., prosumers, energy community or EV parkings) to provide flexibility to any flexibility requesting parties via local market environment. Note that the results of ECOFLEX ecosystem is not solely the output of task 5.1, but also in collaboration with other Work Packages (and project partners). In this deliverable, more attention will be focused on the local market mechanism and optimization methodologies for enabling flexibility valorisation of prosumers in an energy community on a multi-market context by utilizing ECOFLEX ecosystem. The proposed methodology emphasizes on coordination mechanisms among actors (sites, Universal Flexibility Platform, and markets) as well as grid constraints management. The rest of the document is presented as the following: Section 2 overviews the ECOFLEX ecosystem and innovation, Section 3 presents the proposed coordination mechanism and optimization formulations. Section 4 provides the simulation results, and the document is summarized in Section 5.

2. ECOFLEX Ecosystem

2.1 Overview

The ECOFLEX project aims to unlock the potential of electric cars and energy communities to balance the grid in a climate neutral way. To achieve this, multiple aspects are researched, going from the development of new energy management system (EMS) technologies towards the development of a novel platform to provide flexibility via low-voltage assets such as energy communities and e-mobility. The innovative aspect of the project can be described based on figure below:

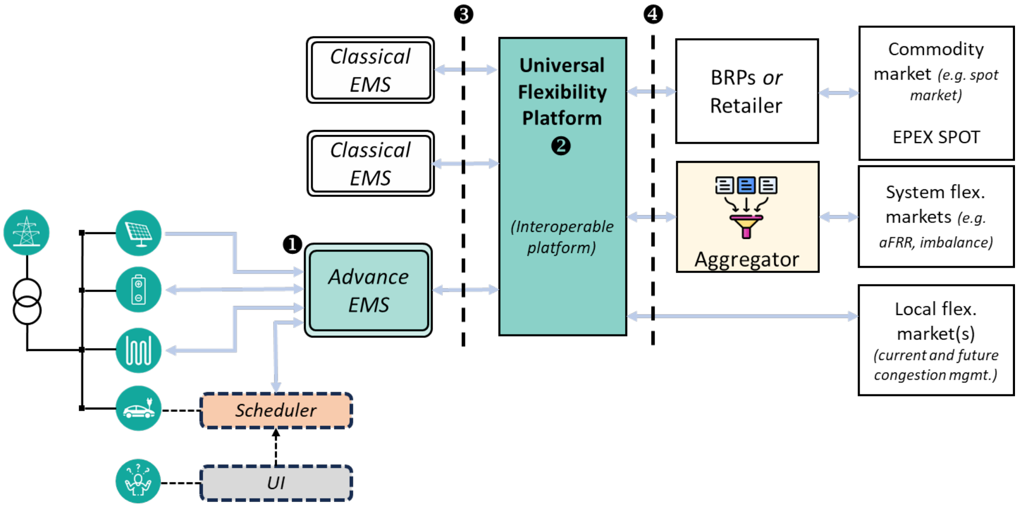

Figure 1 ECOFLEX Ecosystem

The core of the project focuses on unlocking the potential of flexibility services through the development of a universal flexibility platform (UFP). There are four main innovations the project brings (numbered as the picture above):

1. **Advance Energy Management systems (EMS):** Compared to a classical EMS[1], the advance EMS is capable to compute potential flexibility valorization (based on forecast), and communicate with the UFP to participate in flexibility markets (e.g, sending and receiving flexibility offers and setpoints).
2. **Universal Flexibility platform (UFP):** is a platform that can facilitate any assets with flexibility potentials to value its flexibility to different flexibility requesting parties (FRPs), such as aggregator or BRPs. This by providing a generic way of offering, requesting and activating flexibility in various forms, e.g. electrical vehicle (EV) charging, BESS and domesting heating systems.
3. The goal of UFP is to **facilitate flexibility** valorization not exclusively for a local flexibility provider[2] (LFP) with advance EMS, but also for LFP with classical EMS .
4. Lastly, the UFP can be seen as a *bridge* or *intermediary* for customers/LFP to flexibility markets. Hence, the goal of UFP is to **connect LFP to any types of markets** (e.g., aFRR, Imbalance, etc).

As described in the deliverable D3.1 of the project, the ECOFLEX ecosystem models and processes can be designed as generic solutions that can be used for various use cases, for instance for valorization of LFPs in Automatic Frequency Restoration Reserve (aFRR) or imbalance market that differ in mechanisms (described in WP6). For the sake of genericity, a simplified interaction between LFP, UFP and FRPs is illustrated in the Figure 2 and explained below:

---

[1] A classical EMS here is assumed not capable to compute flexibility potential, participate in flexibility markets (e.g., provide flex offer) and communicate with UFP. In addition, a classical EMS typically relies on model-based algorithm such as model predictive control (MPC).

[2] A customer with any flexible assets and EMS can also be called as a local flexibility provider (LFP), this such as an energy community or an EV parking

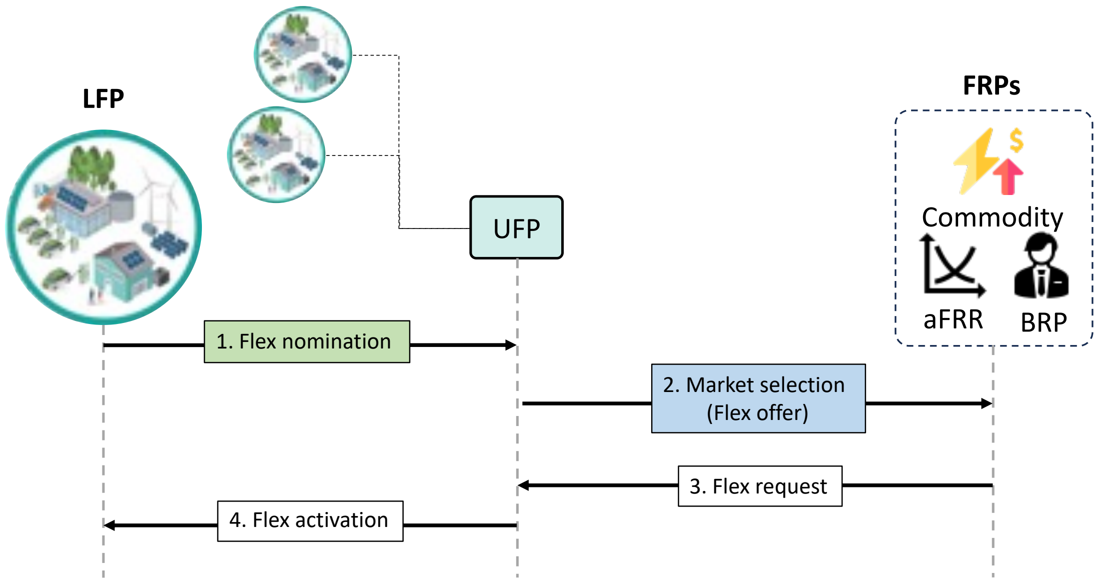

Figure 2 Generic interaction between actors in the ecosystem

1. A site LFP can perform a **flexibility nomination**. It is defined as how much flexibility can a site/LFP provide for a specific time horizon. It is also described by the amount of power (and/or energy), direction (upwards or downwards) and its corresponding price. Further details of flexibility nomination can be found in the deliverable D3.1. Examples of flexibility nomination will also be given in the following sections of this document.
2. Next, the UFP gathers flexibility nominations from all sites/LFPs and to bid (or sell) the aggregated flexibility to FRPs. Depending on the contracts between LFPs or FRPs, it is possible that UFP to perform market selection (e.g., select different FRPs) or doing arbitrage between different markets. Note that, this interaction mechanism can be done technically with the proposed ECOFLEX ecosystem. However, such interaction (e.g., directly aggregating different sites and performing market arbitrage) is still not possible in real-life use cases due to contractual/regulatory reasons. These regulatory challenges are addressed in task 7.3 of the project, and not the scope of this deliverable. This document focuses on theoretical/fundamental research on market mechanisms, by neglecting the regulatory barriers that hinder the implementation in current real-life situation.
3. Once the bid by UFP is accepted, FRPs will send flexibility activation request/signal to the UFP. Depending on the market product, the activation request can be a simple binary decision (e.g., whether activate or not activate the flexibility) or setpoints (such as aFRR).

4. Lastly, the UFP will allocate the flexibility request by FRPs to different sites/LFPs within its portfolio. This to ensure that all the sites can provide flexibility that match the FRPs' request.

2.2 Challenges

The goal of ECOFLEX is to enable flexibility valorization of LFP (e.g., energy communities and electric vehicle parks) mainly in both implicit and explicit-way[3]. This includes participating in balancing markets (e.g., FCR, aFRR or mFRR), going to commodity market, provide balancing services to BRPs or participating in imbalance market. Hence, one of the main challenges is to define the interaction scheme and timeline between EMSs and UFP to allow flexibility valorization that takes into account different market products and their respective timeline. This complexity is illustrated in Figure 3.

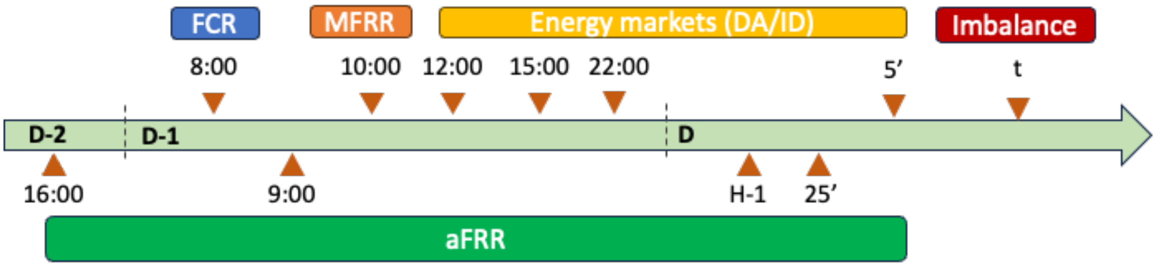

Figure 3 Different market timeline

From each LFP perspective, local grid congestion is also a barrier for flexibility valorization. Although the widespread adoption of DERs can bring many benefits for distribution power systems, it also imposes numerous operational challenges (e.g., reverse power flows, congestion and voltage problems [1]), to distribution system operators (DSOs). For example, a participation of LFP in balancing markets (e.g., aFRR) could increase the flexibility at global grid level, yet it cannot mitigate possible congestion locally at distribution level. Lastly, the last challenge is related to the fact that DERs can be deployed and owned by multiple asset owners/prosumers, particularly in the context of energy communities. From the operational perspective, prosumers with DERs have to ensure that they will not negatively impact the power quality of the grid when performing flexibility valorization. This implies that there is the need of proper coordination between all the actors in the ecosystem to ensure the

---

[3] **Explicit** here means flexibility valorization by participating in external markets (e.g., aFRR). It is different than **implicit** approach, which represents flexibity valorization based on price signals.

flexibility valorization at LFP level can be economically optimal while overcoming potential local grid problems.

To summarize, this deliverable focuses on the research on operational management strategy for **energy communities** to facilitate flexibility valorization in the context of ECOFLEX flexibility ecosystem, by taking into account three main operational challenges:

1. The complexity of market mechanisms due to various implicit and explicit flexibility markets
2. The multi-prosumers characteristic of energy communities
3. Potential local grid congestion due to flexibility valorization at communities

The remainder of this document is organized as follow: section 3 presents the proposed local flexibility market concept, including the mathematical model. Section 4 presents the simulation results and section 5 concludes the document.

3. Two-Stage Local Flexibility Markets

3.1 Definition

The concept of what-so-called as a 'local energy markets' (LEMs), has received growing attention. It represents a decentralised approach to organising electricity markets, which enables trading locally generated electricity and flexibility in virtually or geographically limited areas, like the distribution grid level, neighbourhoods, and small towns or in energy community contexts [5]. In most literatures, the main limitation of existing LEM mechanisms is the incapability of the market clearance to mitigate potential local grid problems, as most of the methods neglect or consider oversimplified grid models to address such problem.

This deliverable proposed a market mechanism to settle energy and flexibility transaction in energy communities. The considered energy community in the research consists of prosumers (e.g., consumers with assets such as solar panels and battery) that act as community members. In such community, each member can exchange/share energy to other members, in addition to conventional retailers. Moreover, community members can also valorise their flexibility to the grid via various implicit and explicit external markets. Both energy sharing and flexibility valorisation is governed by a community manager (CM), who is a third-party entity that has the role to facilitate all the transaction and settlements among community members and external parties (e.g., distribution operator, flexibility requesting parties, etc). The role of CM can also be seen as a *"local market operator"* and this role can be facilitated with the **universal flexibility platform (UFP)** that is developed in ECOFLEX. Please refer to deliverable of WP3 for more detailed functionality of UFP.

3.2 Mathematical Model

This subsection presents the mathematical models of the considered energy community, distribution power grid as well as local assets (PV and ESS). In this research, the dispatchable/controllable asset is the ESS, which is the main asset that provide flexibility. Electrical loads (consumption) and PVs are non-dispatchable, which are operated in a fixed power factor of 0.95. Table 1 presents the nomenclature of the main sets, parameters, and variables used in this document.

Table 1 Nomenclature

Sets	
$\mathcal{N}$	Set of Buses
$\mathcal{H}, \mathcal{B} \subset \mathcal{N}$	Set of prosumers, and prosumers with ESS
$\mathcal{E} \subset \mathcal{N} \times \mathcal{N}$	Set of lines
$\mathcal{T}$	Set of times in the considered time horizon
Parameters and Variables	
$v_{i,t}, \nu_{i,t}$	Voltage and squared voltage of bus *i* at time *t*
$\ell_{ij,t}, p_{ij,t}, q_{ij,t}$	Squared current, active and reactive power flowing from bus *i* to bus *j* or line (*i, j*) at time *t*
$r_{ij},\ x_{ij}$	Resistance and reactance of line (*i, j*)
$p_{i,t}^{\mathrm{ld}},\ q_{i,t}^{\mathrm{ld}}$	Active and reactive power of load at bus *i* at time *t*
$p_{i,t}^{\mathrm{pv}},\ q_{i,t}^{\mathrm{pv}}$	Active and reactive power of PV at bus *i* at time *t*
$p_{i,t}^{\mathrm{st}}$	Active power of ESS at bus *i* at time *t*
$\overline{e}_{i}^{\mathrm{st}}$	Energy capacity of ESS at bus *i*
$soc_{i,t}$	State of charge (%) of ESS at bus *i* at time *t*
$\eta_i^+,\ \eta_i^-$	Charging and discharging efficiency (%) of ESS at bus *i*

3.2.1 Grid model

The research focuses on an energy community connected in a distribution grid with a radial configuration. Such grid can be modelled as a graph $\mathcal{G} = \{\mathcal{N}, \mathcal{E}\}$, where denotes the set of buses and describe the line/branch. A radial distribution grid can be modelled as a set of BranchFlow equations [6] as follow:

$$p_{ij,t} = \sum_{k:(j,k)\in\mathcal{E}} p_{jk,t} + r_{ij}\ell_{ij,t} + p^{\text{ld}}_{j,t} - p^{\text{pv}}_{j,t} + p^{\text{st}}_{j,t} \tag{1a}$$

$$q_{ij,t} = \sum_{k:(j,k)\in\mathcal{E}} q_{jk,t} + x_{ij}\ell_{ij,t} + q^{\text{ld}}_{j,t} + q^{\text{pv}}_{j,t} \tag{1b}$$

$$\nu_{j,t} = \nu_{i,t} - 2(r_{ij}p_{ij,t} + x_{ij}q_{ij,t}) + (r^2_{ij} + x^2_{ij})\ell_{ij,t} \tag{1c}$$

It is assumed that the battery only produces an active power $p^{\text{st}}_{j,t}$. The net power at each prosumer level (i.e., the net sum of load, battery and PV power), can also be described as a contractual power:

$$\underbrace{p^{\text{ld}}_{j,t} - p^{\text{pv}}_{j,t} + p^{\text{st}}_{j,t}}_{\text{physical power flows}} = \underbrace{p^{\text{gd}^+}_{i,t} + p^{\text{cm}^+}_{i,t} - p^{\text{gd}^-}_{i,t} - p^{\text{cm}^-}_{i,t}}_{\text{contractual power flows}} \tag{2}$$

Where $p^{\text{gd}^+}_{i,t}$ and $p^{\text{gd}^-}_{i,t}$ denote the energy purchased and sold to the grid/conventional retailer, while $p^{\text{cm}^+}_{i,t}$ and $p^{\text{cm}^-}_{i,t}$ denote the transaction within the community.

3.2.2 Energy storage model

In this deliverable, the ESS is modelled as community storages and located dispersedly within a community. A storage is considered as the flexible asset, which allow community to participate in flexibility markets. As explained in section 2, providing flexibility services, especially upward regulation during high PV production may cause overvoltage issue at a local/community level. To mitigate this issue, ESSs are optimized to charge/discharge in a coordinated manner, depending on the level of PV production as well as where the ESS is located in the grid.

For each ESS $i \in \mathcal{B}$ and each time $t \in \mathcal{T}$, the active power of each ESS can be disaggregated into a discharging power $p^{\text{dchg}}_{i,t(s)}$ and charging power $p^{\text{chg}}_{i,t(s)}$. The subscript (*s*) defines the scenario which will be introduced in the next subsection.

$$p^{\text{st}}_{i,t} = p^{\text{chg}}_{i,t(s)} - p^{\text{dchg}}_{i,t(s)} \tag{3a}$$

$$0 \le p^{\text{chg}}_{i,t(s)}, p^{\text{dchg}}_{i,t(s)} \le \overline{p}^{\text{st}}_{i,t} \tag{3b}$$

Where $\overline{p}^{\text{st}}_{i,t}$ denotes the maximum active power of ESS *i*. the state of charge (SoC) of the ESS is updated as (4) and is maintained as in (5), where Δt denotes the timestep.

$$soc_{i,t+1(s)} = soc_{i,t(s)} + \left(p_{i,t(s)}^{\mathrm{chg}} \eta_i^{\mathrm{chg}} - \frac{p_{i,t(s)}^{\mathrm{dchg}}}{\eta_i^{\mathrm{dchg}}} \right) \frac{100}{\overline{e}_i^{\mathrm{st}}} \cdot \frac{\Delta t}{60} \tag{4}$$

$$0\% \leq soc_{i,t(s)} \leq 100\% \tag{5}$$

3.2.2 Energy Community Operation and Market models

In this work, a two-stage operation mechanism is introduced for energy communities. The goal of the proposed mechanism is to decouple between energy sharing and flexibility services. The first stage is modelled like day-ahead market mechanism, where each member in the community will bid and offer the amount of energy they are willing to exchange in the next day as well as the maximum amount of power they can provide for flexibility services. The second stage is modelled like an intraday mechanism, where the community will determine the optimal energy exchange and flexibility service allocations depending on near real-time situation (e.g., forecast error) and commitments done by each community members in stage 1/day-ahead. In the considered operation scheme, there exists a community manager (CM) who is responsible to assist the energy exchange in the community and acts as a facilitator between the members and the market. The overall interaction is shown in Figure 4.

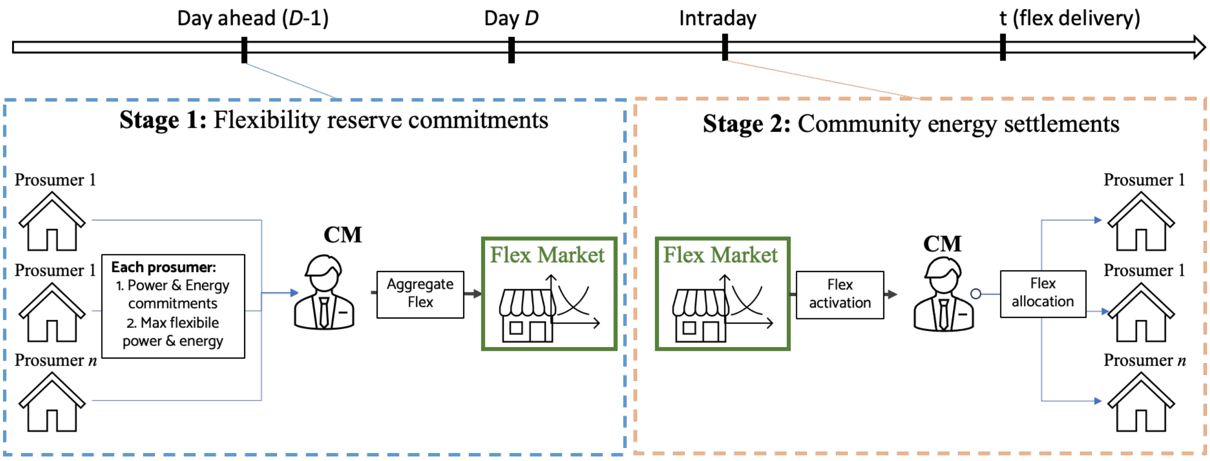

Figure 4 The proposed two-stage mechanism

A. Stage 1: Day-ahead Optimization (flexibility reserve commitment)

The goal of stage 1 is to collect commitments from prosumers (i.e., community members) on energy exchange and providing flexibility service in the next day. The energy sharing scheme is adapted based in previous works [1], where community members can trade energy within each other using commitment mechanism, similar to day-ahead wholesale energy market. Compared to the previous works, flexibility reservation mechanism is formulated in this optimization model. The flexibility reservation method is based on a typical approach of existing flexibility markets, such as the aFRR mechanism in Belgium. AfRR is considered in this study as it is regarded as one of the complex markets to participate, as it consists of multiple stages – from power reservation, energy bidding, to actual flex activation.

In the proposed interaction model, an energy community (via CM), will act as a facilitator to the aFRR market. Therefore, CM will play the role of market bidder, using the aggregated capacity commitments made by the community members. For simplicity reason, we assume that the CM will always bid at the lowest capacity and energy prices in the aFRR market. Hence, the bid placed by the community will always be selected as well as the reserved flexible capacity will always be activated.

This stage 1 (i.e., reserve commitment) problem is formulized as an optimization problem with the main objective to maximize overall prosumers' expected revenues from flexibility services (capacity reservation and flexibility activation). For the simplicity of the formulation, it is also assumed that providing flexibility services is more financially attractive compared to energy sharing/self-consumption. Note that, this formulation of revenue maximation can still be more extended, by incorporating additional revenue model from energy sharing/self-consumption as part of the objective function (as in [1]).

In order to take into consideration grid constraints, a second-order conic programming (SOCP) relaxation of the grid model [7] is incorporated in the optimization formulation. Therefore, an additional objective function (i.e., grid losses minimization) is added to ensure the validity of the SOCP model. Let *d* be a day in the considered time horizon $\mathcal{T}$, and $\mathcal{T}_d \subset \mathcal{T}$ denotes the time horizon at day *d.* For each day *d,* the stage 1 is formulated as the following:

$$\min \sum_{t \in \mathcal{T}_d^{\text{flex}}} \sum_{i \in \mathcal{B}} p_{i,t}^{\text{flex}} \pi_t^{\text{flex}} + \beta \sum_{t \in \mathcal{T}_d} \sum_{(i,j) \in \mathcal{E}} \ell_{ij,t} \tag{6}$$

Subject to:

1. Grid Model (1), $\forall t \in \mathcal{T}_d, \forall (i,j) \in \mathcal{E}$

2. Branch current relaxation, $\forall t \in \mathcal{T}_d, \forall (i,j) \in \mathcal{E}$:

$$\ell_{ij,t} \geq \frac{p_{ij,t}^2 + q_{ij,t}^2}{\nu_{i,t}} \tag{7}$$

3. Voltage operating limits (in p.u), $\forall t \in \mathcal{T}_d, \forall i \in \mathcal{N}$:

$$0.9 \leq v_{i,t} \leq 1.1 \tag{8}$$

4. Virtual flexible capacity reserve, $\forall t \in \mathcal{T}_d^{\text{flex}}, \forall i \in \mathcal{B}$:

$$e_{i,t+1}^{\text{flex}} = e_{i,t}^{\text{flex}} - \frac{p_{i,t}^{\text{flex}}}{\eta_i^{\text{flex}}} \cdot \frac{\Delta t}{60} \tag{9a}$$

$$0 \leq e_{i,t}^{\text{flex}} \leq \overline{e}_i^{\text{flex}} \tag{9b}$$

$$0 \leq p_{i,t}^{\text{flex}} \leq \overline{p}_i^{\text{flex}} \tag{9c}$$

5. External market constrains, $\forall t \in \mathcal{T}_d^{\text{flex}}$:

$\sum_{i \in \mathcal{B}} p_{i,t}^{\text{flex}} = p_d^{\text{bid}}$	(10a)
$\underline{p}^{\text{flex}} \phi_d \leq \sum_{i \in \mathcal{B}} p_{i,t}^{\text{flex}} \leq \sum_{i \in \mathcal{B}} \overline{p}_i^{\text{flex}} \cdot \phi_d$	(10b)

First of all, β in (6) provides weight between the two objective functions. This parameter is introduced to ensure the validity of the SOCP problem [7]. The set $\mathcal{T}_{\text{flex}}^{d} \subset \mathcal{T}$ is the time horizon of the flexibility market where the community participates. As described, we focus on the aFRR-like market, where $\mathcal{T}_{\text{flex}}^{d}$ corresponds to a typical 4-hour window. Specifically, for this study, we consider a participation of a participation in upward per-cctu afRR market from 12:00 to 16:00. The reason of this specific market and time horizon because it represents the time where the PVs have the highest production. Consequently, providing aFRR upward services with ESS in this timeframe could induce overvoltage problem at the local level. Our goal is then to show that the proposed methodology can mitigate such issue.

The optimization formulation incorporates the grid model as part of the constraints, in which (7) is utilized to convexify the problem and (8) ensures the local grid voltage remains within the acceptable limits. A virtual flexibility reserve (9) is introduced, where it gives constraints to the amount of flexible power and energy for each member in a community. It can be seen that the constraint (9a) is similar to the ESS SoC update (4), without the power charging term. This because the virtual flexibility reserve is modeled like a ESS, where the concept of upward flexible capacity $p_{i,t}^{\text{flex}}$ has a similar concept to BESS discharging power, and it is limited to amount of energy available for flexibility services $\overline{e}_i^{\text{flex}}$. Similarly, downward capacity can also be modeled as ESS charging, as it will increase $\overline{e}_i^{\text{flex}}$. As the focus of this study is upward flexibility services, hence the downward capability is not modeled.

Each prosumer that is willing to participate in the flexibility valorization has to submit its maximum flexible capacity $\overline{p}_i^{\text{flex}}$ and energy $\overline{e}_i^{\text{flex}}$ commitments. These are parameters that have to submitted by each prosumer. Indeed, to obtain these parameters, forecast methodologies to do arbitrage (e.g., to provide flexibility or doing self-consumption) can be performed. However, it is not covered in this document, as the focus of this deliverable is solely on the market mechanism. The forecast methodology is covered in deliverable D2.3.

Furthermore, the proposed optimization problem incorporates the grid model as part of the constraints (7), with (8) will ensure that the bus voltages remain within their limits. Lastly, the constraints (10) represent the external market constraints. The p_d^{bid} is the aggregate amount of power from each community member ($p_{i,t}^{\text{flex}}$) that eventually will be offered to the market. The community's decision to place the bid in the market at day *d* is denoted by $\phi_d \in \{0,1\}$, with 1 means to participate and 0 not to participate. Lastly, $\underline{p}^{\text{flex}}$ denotes the minimum capacity allowed to participate in the market.

B. Stage 2: Intraday Optimization (Community Settlements)

The second stage considers similar operation scheme as [1], where prosumers in the community can trade energy with other members in addition to transaction with conventional energy retailers. This type of community operation typically relies on look-ahead (e.g., day-ahead) energy settlements and utilize penalty scheme if the actual energy transaction deviate from the commitments. In this deliverable, a deterministic scenario is considered, which means that no penalty scheme is incorporated. For simplicity, we assume that the flexibility settlements in stage 1 can be fully dispatched, as well as perfect forecast of PV and loads.

For each day *d,* the energy settlement problem is formulized as:

$$\min \sum_{t\in\mathcal{T}_d}\sum_{i\in\mathcal{H}}\left(p_{i,t}^{\text{cm}^+}\pi_t^{\text{cm}^+} - p_{i,t}^{\text{cm}^-}\pi_t^{\text{cm}^-} + p_{i,t}^{\text{gd}^+}\pi_t^{\text{gd}^+} - p_{i,t}^{\text{gd}^-}\pi_t^{\text{gd}^-}\right) + \beta\sum_{t\in\mathcal{T}_d}\sum_{(i,j)\in\mathcal{E}}\ell_{ij,t} \quad (11)$$

Subject to:

1. Grid Model (1), $\forall t\in\mathcal{T}_d, \forall(i,j)\in\mathcal{E}$

2. Branch current relaxation, $\forall t\in\mathcal{T}_d, \forall(i,j)\in\mathcal{E}$

3. Voltage operating limits (8), $\forall t\in\mathcal{T}_d, \forall i\in\mathcal{N}$

4. Baseline profile (s = 0), $\forall t\in\mathcal{T}_d \ \forall i\in\mathcal{B}$:

$$p_{i,t(0)}^{\text{chg}} = p_{i,t}^{\text{st}^{+}} \tag{12a}$$

$$p_{i,t(0)}^{\text{dchg}} = p_{i,t}^{\text{st}^{-}} \tag{12b}$$

and ESS constraints (3) – (5)

5. Flexibility activation scenario (*s* = 1), $\forall t \in \mathcal{T}_d \ \forall i \in \mathcal{B}$:

$$p_{i,t(1)}^{\text{chg}} = p_{i,t}^{\text{st}^{+}} - p_{i,t}^{\text{flex}} \alpha_{i,t} \tag{13a}$$

$$p_{i,t(1)}^{\text{dchg}} = p_{i,t}^{\text{st}^{-}} + p_{i,t}^{\text{flex}} (1 - \alpha_{i,t}) \tag{13b}$$

and ESS constraints (3) – (5)

6. ESS charging and discharging limits, $\forall t \in \mathcal{T}_d \ \forall i \in \mathcal{B}$:

$$p_{i,t}^{\text{flex}} \alpha_{i,t} \leq p_{i,t}^{\text{st}^{+}} \leq \overline{p}_{i,t}^{\text{st}} \alpha_{i,t} \tag{14a}$$

$$p_{i,t}^{\text{st}^{-}} \leq (\overline{p}_{i,t}^{\text{st}} - p_{i,t}^{\text{flex}})(1 - \alpha_{i,t}) \tag{14b}$$

The first term of objective (11) aims to minimize the overall energy cost among the members. Similar to (6), losses minimization is also added in the objective due to consideration of grid constraints with SOCP formulation. In this formulation, scenarios (*s*) are defined, where *s = 0* refer to baseline scenario (i.e., if the flexibility is not requested to be activated) and *s = 1* is the scenario if the flexibility is activated. The two scenarios will provide scheduling plan for the ESS and ensure ESS' SoC can always be maintained within the limits despite the flexibility is fully/partially/or even not activated. Moreover, defining baseline scenario is also essential for reporting purposes to the market/system operator (such as in aFRR where the flexibility service provider has to provide the baseline profile). Lastly, (14a) provides limit to the charging power of the ESS, with $\alpha_{i,t} \in \{0,1\}$ decides whether the ESS *i* should charge or discharge at time *t* by considering the flexibility commitments $p_{i,t}^{\text{flex}}$. If the ESS is charging, $p_{i,t}^{\text{flex}}$ is set as the lower bound of the charging power to allow some reserve for power reduction for the purpose of upward flexibility commitments. Similarly, (14b) limits in case the ESS discharges and ensure there is enough power limits to provide the upward flexibility services in case it is activated.

4. Simulations and Results

In this section, the proposed two-stage management strategy is simulated in a 11-bus distribution system [8], as shown in Figure 5. It consists of six prosumers that organized as a community. The load profiles are adapted from [9] and the PV profile are obtained from [10].

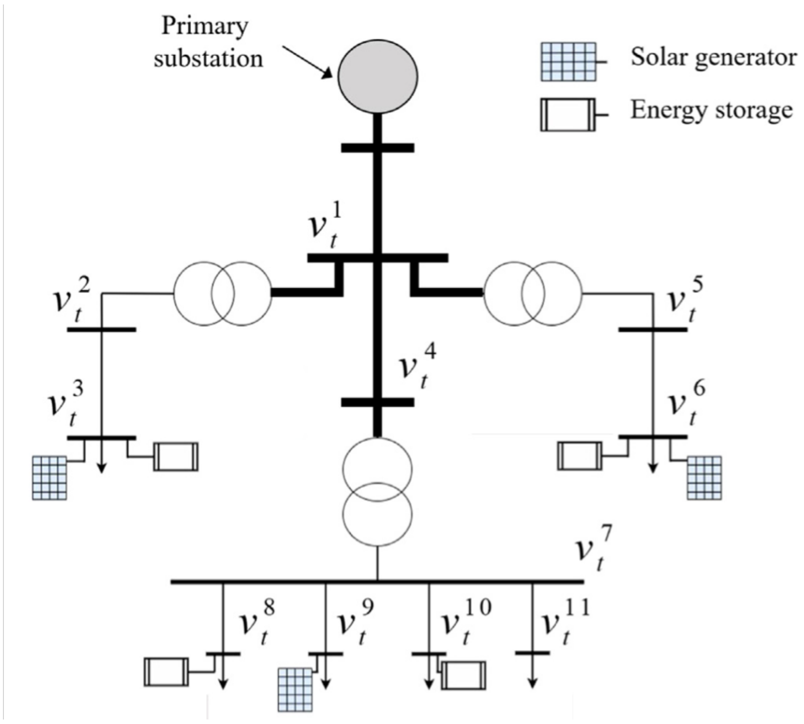

Figure 5 The 11-bus system

In the considered test case, the energy purchase price from the retailer ($\pi_t^{\mathrm{gd}^+}$) follows the time-of-use (ToU) pricing, which are 7.97 c€/kWh and 11.75 c€/kWh for outside and during peak hours, respectively. The excess energy from the PV (or battery) can also be sold to the retailer with a lower rate of 6.5 c€/kWh. In addition, prosumers/community members can benefit for the energy exchange within the community, where they can purchase and sell energy with more attractive rates than the conventional retailer, which are fixed at 7.5 c€/kWh and 7 c€/kWh respectively. For flexibility valorization, it is assumed that providing flexibility gives the highest incentives from the customer, compared to self-consumption or exchanging energy within the community. The flexibility is incentivized based on the energy delivered, which is 10 c€/kWh. Note that for simplicity reason, capacity-based remuneration is not considered in this study, and we assume that every upward aFRR bids by the community in the market will always be selected or activated.

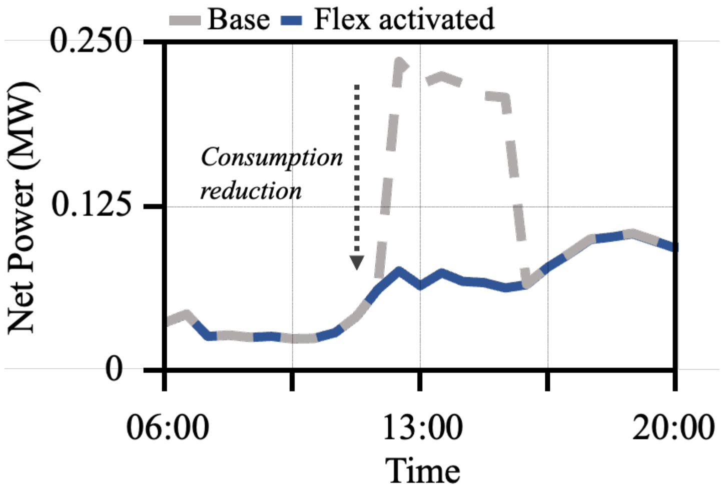

Figure 6 Sample net profile of a prosumer: with vs without flexibility activation

In this study, a simulation with a time horizon of two-weeks is conducted. In each day, a community will place an upward aFRR bid for the next day specifically only for valorization between 12:00 to 16:00 that represent the peak PV production. Figure 6 shows a sample day of a prosumer's net power profile. The base profile illustrates the baseline, i.e., the net power profile if the flexibility is not activated. Since the flexibility is activated, it is represented by the solid blue line, which shows that there is a reduction in net profile since the ESS discharges. The ESS discharging action is depicted in Figure 7, where the battery discharges at 12:00 which corresponds to the starting period of flexibility activation. Moreover, it can be seen that the dispatching strategy of the ESS differs with and without (base) flexibility activation. However, this highlights that the proposed methodology is able to determine dispatching strategy of the ESS despite of different in scenarios.

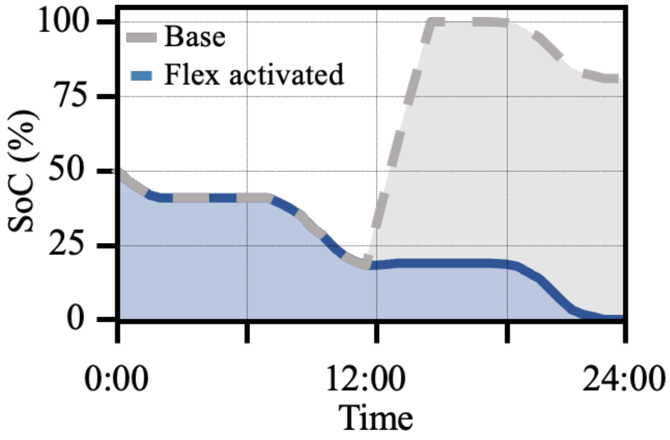

Figure 7 ESS SoC profile comparison with and without flexibility activation

Furthermore, the effectiveness of the proposed methodology can also be seen in Figure 8 which represent a sample bus voltage. Although the ESS discharges during the flexibility activation period (alongside with the peak PV production), the proposed methodology can effectively mitigate overvoltage violations. Overvoltage may occur without considering grid constraints model in the proposed methodology, i.e., eliminating the losses term in the objective (6) and (11) as well as removing grid-related models in the optimization formulation.

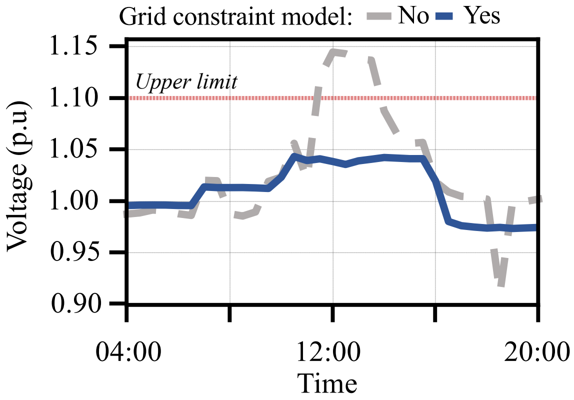

Figure 8 Voltage profile with and without grid model consideration

Despite its effectiveness, fairness is one of the main challenges when considering grid constraint management in flexibility valorization scheme within communities. This is illustrated in Figure 9 where there is significant difference of flexibility activation with and without incorporating grid constraint management. Without considering grid constraints model, all ESSs provide equal flexibility contribution. However, incorporating grid model could lead to economic disadvantage to some prosumers, especially for the ones who are located in the weaker parts of the grid. These prosumers are reflected as prosumer 3 and 6 as in Figure 9 whose more prone to voltage problems, compared to other prosumers. Consequently, these prosumers are not able to valorize flexibility as much as the other prosumers.

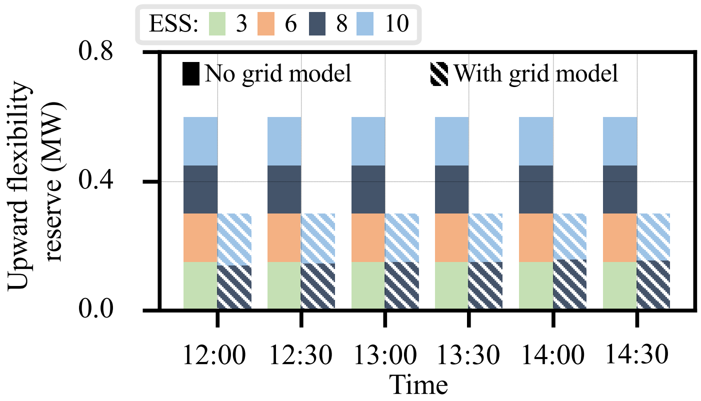

Figure 9 Flexibility allocation among different ESS

Unfair contribution can also be seen in Figure 10, where prosumers 3 and 6 contribute less flexibility valorization compared to prosumer 8 and 10. As previously mentioned, this due to the fact that these two prosumers are located in the weaker part of the grid and could impose overvoltage problem if they provide upward flexibility services.

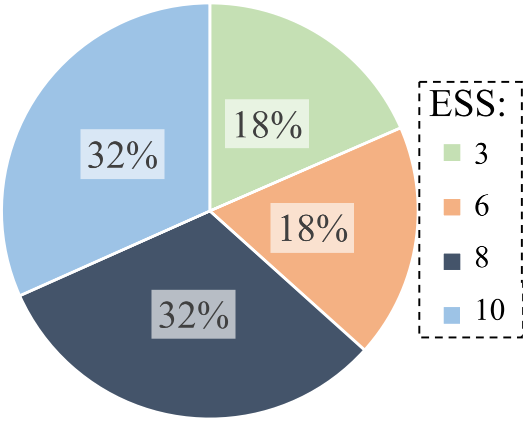

Figure 10 Total amount of flexible energy valorised by each ESS over two weeks

5. Conclusion & Future Works

This deliverable presents the ECOFLEX ecosystem and a market-based methodology to allow prosumers in the community to provide grid-aware flexibility services. Particularly, the study also investigates how upward flexibility valorization could cause voltage violations, especially during the period with high local/PV production. The simulation show that the proposed two-stage methodology were effectively able to facilitate flexibility valorization of prosumers in a community, while grid constraints violation can still be mitigated. However, the challenge remains on the fairness aspect, where prosumers located in a weaker part of the grid (i.e., more sensitive to voltage violations) are not able to provide more flexibility compared to other prosumers.

The research work on this deliverable can be extended to several areas. Firstly, the proposed two-stage methodology can be more extended by considering other market time horizon and flexibility direction (i.e., downward aFRR) and to take into account different types of markets (e.g., commodity day-ahead market). By doing this, a community can do market arbitrage and potentially optimize more the economic benefit that they can receive from flexibility services. Regarding the fairness aspect, other incentive mechanism such as penalty/reward scheme can be implemented in the second stage. Other mitigation strategy such, as collectively investing and placing ESS strategically also can be done, to compensate prosumers that are located in the weaker part of the grid.

References

[1] M. A. Putratama, et all, "A Three-Stage Strategy With Settlement for an Energy Community Management Under Grid Constraints," in IEEE Transactions on Smart Grid, 2023.

[2] ebIX, “Overview of energy flexibility services,” 2020.

[3] P. Olivella-Rosell, P. Lloret-Gallego, I. Munn´ e-Collado, R. Villafafila-Robles, A. Sumper, S. Ø. Ottessen, J. Rajasekharan, and B. A. Bremdal, “Local flexibility market design for aggregators providing multiple flexibility services at distribution network level,” Energies, vol. 11, no. 4, p. 822, 2018.

[4] S. Ødegaard Ottesen, A. Tomasgard, and S.-E. Fleten, “Multi market bidding strategies for demand side flexibility aggregators in electricity markets,” Energy, vol. 149, pp. 120–134, 2018.

[5] Ting Chen, Frederik Vandendriessche, “Enabling independent flexibility service providers to participate in electricity markets: A legal analysis of the Belgium case,” in Utilities Policy, 2023.

[6] S. H. Low, “Convex relaxation of optimal power flow—part i: For-mulations and equivalence,” IEEE Transactions on Control of Network Systems, vol. 1, no. 1, pp. 15–27, 2014.

[7] M. A. Putratama, R. Rigo-Mariani, V. Debusschere, and Y. Besanger, “Parameter Tuning for LV Centralized and Distributed Voltage Control with High PV Production,” in IEEE PowerTech, 2021, pp. 1–6.

[8] A. Petrusev, M. A. Putratama, R. Rigo-Mariani, V. Debusschere, P. Reignier, and N. Hadjsaid, “Reinforcement learning for robust voltage control in distribution grids under uncertainties,” Sustainable Energy, Grids and Networks, vol. 33, p. 100959, 2023.

[9] “Smartmeter energy consumption data in london households.” [Online]. Available: https://data.london.gov.uk/dataset/smartmeter-energy-use-data-in-london-households

[10] M. Sengupta, Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby,“The national solar radiation data base (nsrdb),” Renewable and Sustainable Energy Reviews, vol. 89, pp. 51–60, 2018.