D5.2 – Performance assessment of current and new market designs and trading mechanisms for Local Energy Communities (Case Study A)

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TradeRES

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1.0	29.08.2022	Public	This report will present and analyse the results obtained with the current and new markets designs for Local Energy Communities.

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Executive Summary

The present deliverable was developed as part of the research activities of the TradeRES project Task 5.2 – Local Energy Communities: Case Study A.

This report presents the first version of the deliverable 5.2, which outlines the methodologies and the case study scenarios, which will be simulated in the final iteration of this deliverable. Relevant and realistic datasets that will be used to carry out these simulations are also discussed.

The methodologies provided in this deliverable illustrate the proposed market designs of the case studies that will be simulated in the final iteration. This includes descriptions of transactions within the market, the behaviour of participants, bi-level modelling of interactions within local markets, and a demo website to illustrate how blockchain technology can be used to facilitate trading in local energy communities.

Finally, the case studies that will be simulated in the final iteration of this deliverable are described. The baseline case of market players trading with the grid/energy suppliers is investigated in detail, as this will be the baseline to which the proposed market designs will be compared. As such, an analysis of economic benefits to participants within the local energy market compared to the peer to grid scenario; indicating favourable results for participants in local energy communities.

Table of Contents

List of Tables

List of Figures

List of Acronyms

LEC	Local Energy Community
BESS	Battery Energy Storage System
bY	BitYoga
CER	Commission for Energy Regulation
CHP	Combined Heat & Power
DA	Day-ahead
ES	Energy storage owner
EV	Electrical Vehicle
FC	Flexible consumer
FiT	Feed-in-Tariff
IDMA	Intelligent Data Mining and Analysis
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISA	Intelligent System Applications
KKT	Karush-Kuhn-Tucker
LCOE	Levelized cost of electricity
LEM	Local Energy Market
LES	Local Energy System
LL	Multiple lower level
LPG	Liquefied petroleum gas
MG	Micro-generator
MILP	Mixed-integer linear programming
MPEC	Mathematical problem with equilibrium constraints
NaN	Not a number
P2G	Peer-to-grid
P2P	Peer-to-peer
PES	Power & Energy Society
Photovoltaic	PV
PRODIST	Distribution Procedures
ToU	Time-of-Use
UiS	University of Stavanger
UL	Single upper level
vRES	variable Renewable Energy Sources
WG	Working Group

1. Introduction

The present deliverable was developed as part of the research activities of the TradeRES project *Task 5.2 – Local Energy Communities: Case Study A* under work package 5, "*Performance assessment of the market(s) design(s). Application of the open-access tools to characteristic case studies*". This report constitutes deliverable D5.2.

One way of increasing production of renewable energy is to encourage regular consumers to become prosumers. To facilitate this, Local Energy Communities (LECs)[1] can serve as an arena in which consumers can take control over their own energy acquisition and production. In these communities there will be a greater incentive for people to produce and consume energy locally due to the potential economic benefits. This serves as the foundation of a local energy market, where members can trade energy amongst themselves. Having local markets allows regional or national grids to be more flexible due to the increased power generation and storage capacity. The members will also be able to exercise greater control over their own energy consumption by being able to view and compare prices on the local market to that of regional or national markets in real time.

There are many different market designs and methodologies previously defined for LECs. In this deliverable we focus on the most relevant market designs for this case study. The end goal of the task is to simulate these market designs using real data and compare their performances to determine which designs are most viable. In addition to this, a possible means of facilitating trade is discussed, in the form of a blockchain system.

This deliverable focuses on defining the case studies that will be simulated in the second iteration. These include peer-to-grid energy trading, centralised local energy markets, a centralised peer-to-peer market, and auction-based energy trading.

Section 2 describes the datasets available for the simulations to be performed in the next iteration. Then, Section 3 discusses multiple methodologies behind the market designs to be simulated, and how to facilitate trade. Section 4 explains the case studies that will be simulated in the next iteration with a focus on the baseline peer to grid scenario, and centralised local energy markets. In section 5, some final remarks are provided.

[1] As defined in Article 2 of the *Directive EU 2019/944 on common rules for the internal market for electricity* (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0944&from=EN)

2. Available Data

Having relevant and high-quality data is the first step to a successful simulation, and hence an important step towards the performance analysis of market designs. This section describes data available for use in the second iteration of this deliverable. The final subsection provides a table that summarises the datasets discussed in the other subsections.

2.1 UiS Energy Lab Apartments

Location: University of Stavanger, Norway

Parameters available: power consumption, power generation, weather data

Measurement period: 2019-2022

Temporal resolution: 5 min, 15 min, 1 hour

Type of aggregation (Building, house, etc.): Small apartment buildings

Overall Quality: Some missing data for one solar panel and wind turbine

Description: Consumption and generation for six small apartments at the University of Stavanger campus.

On the campus of the University of Stavanger, there are six small apartments that students can rent, which are part of the Future Energy Lab [1]. This building has two shared solar panels and a small wind turbine. The data consists of solar panel data from both solar panels, the wind turbine, and the aggregated consumption of all the small apartments. It is also a pilot project for wider sustainable developments in the area [2]. The data was acquired through the University of Stavanger (UiS) by bY.

The time resolution of this data is one hour for the consumption, and 5 minutes for the renewable power generated. For the purposes of this project, we aggregate all data to 15-minute intervals. In addition to these data, we also have access to historical tariff data from the local area, which is necessary to create a market simulation.

The main disadvantages with this data are that consumption is aggregated across all apartments, and that there is no indication of how much of the load is flexible vs. non-flexible. Each data source is also hosted on a different platform, which makes it necessary to clean and combine the data.

2.2 IEEE PES ISA Open Data Sets

Location: Portugal, Brazil, EU

Parameters available: power consumption, power generation, EV's state of charge, weather data

Measurement period: 2000-2009, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2019, 2020

Temporal resolution: 5 sec, 10 sec, 1 min, 5 min, 15 min, 1 hour

Type of aggregation (Building, house, etc.): Houses, office buildings, commercial buildings, EVs, PV generation, Wind generation

Overall Quality: Some missing data and non-linearity

Link: http://site.ieee.org/pes-iss/data-sets

Description: A collection of open datasets from various regions and aggregation.

The Institute of Electrical and Electronics Engineers (IEEE) Power & Energy Society (PES) Intelligent System Applications (ISA) subcommittee [3] investigates the development and applications of intelligent system methodologies and tools for problem-solving in power system engineering. These intelligent systems techniques include expert systems, knowledge engineering, artificial neural networks, fuzzy logic, machine learning, evolutionary algorithms, and heuristic search methods. The IEEE Working Group (WG) on Intelligent Data Mining and Analysis (IDMA) [4] makes power and energy-related data sets available whenever confidentiality and data property issues do not prevent their public use. These data are intended to be used by researchers and other professionals working in power and energy related areas and requiring data for design, development, test, and validation purposes. These data should not be used for commercial purposes. The public datasets are permanently available at http://site.ieee.org/pes-iss/data-sets. Data can be used in research and development activities and the obtained results can be published in scientific publications. The IDMA WG public data sets provide access to data from the following areas: Consumption, Electric Vehicles, Power Quality, Photovoltaic (PV) Generation, Reliability, Weather data, Wind-based Generation, and General Energy data.

The Consumption data include: 10 private households, 4 offices, 1 commercial building, among others, with sampling periods ranging from 5 seconds to 15 minutes and different installation settings. The Electric Vehicles (EVs) data includes 3 different databases with 1800, 34 and 15 EVs, respectively, with multiple parameters and different time resolutions. The Power Quality dataset gathers a database with 1380 files of current, voltage and active power measurements (a total of 460 laboratorial essays). All voltage waveforms were configured in accordance with the IEEE, IEC and PRODIST (Brazilian) standards, relating to the harmonic limits. The PV Generation data includes four databases from ISEP's PV data for different years and with different generation capacity. It also includes a database from Enerq-USP (southeast of Brazil). for different periods of time (summer vs. winter). The Reliability data includes a 10-year (2000-2009) outage database for generators, lines/cables, and transformers for IEEE Reliability 24 bus test system. The reliability data includes a 10-year (2000-2009) fault outage database for generators, lines/cables, and transformers' reliability test system, i.e., IEEE Reliability 24 bus. The Weather Data gathers data from multiple sources regarding solar radiation data, wind speed, and ISEP's weather station, and Florianopolis (southern Brazil), São Martinho da Serra (southern Brazil), Brasilia (midwestern Brazil), and Petrolina (northeast Brazil) weather stations among others. The Wind-based Generation dataset includes the values of the wind speed, recorded with time intervals of 10 minutes during the entire year of 2011 at ISEP, located at Porto, Portugal. Finally, the General Energy Data dataset gathers different public datasets for the energy domain.

2.3 Data from the Commission for Energy Regulation (CER)

Location: Ireland
Parameters available: Energy consumption data and survey answers
Measurement period: 2009-2010

Temporal resolution: 30 minutes
Type of aggregation (Building, house, etc.): Houses
Overall Quality: Good
Link: https://www.ucd.ie/issda/data/commissionforenergyregulationcer/

Description: Irish consumption data of 3000 houses during 2009-2019.

The CER Smart Metering Project obtained households' consumption data from Ireland. The data covers a period between 2009 and 2010 with a temporal resolution of 30 minutes. It consists of smart meter household aggregated data of energy (MWh). It presents overall cleaned data (few not a numbers - NaNs) for over 3000 houses. These data also contain a survey on social and economic aspects, with questions such as: *"how old your home? how do you heat and heat water in your home? and how you cook?"*. The main disadvantage is that there is a need to analyse the survey data to infer lower-level appliance ownership and social and economic metadata. Flexible and inflexible consumption must be extrapolated from the survey and the consumption behaviour of every house.

2.4 Elergone Project, NORTE-07-0202-FEDER-038564

Location: Portugal
Parameters available: Power consumption
Measurement period: 2011-2014
Temporal resolution: 15 min
Type of aggregation (Building, house, etc.): Medium tension aggregation
Overall Quality: Good in 2012 and 2013
Link: https://archive.ics.uci.edu/ml/datasets/ElectricityLoadDiagrams20112014\#
Description: Aggregated consumption data of 370 medium voltage Portuguese consumers.

This project monitored the data of 370 Portuguese medium voltage consumers from the period between 2011 to 2014 with a temporal resolution of 15 minutes [5]. These data cover the consumption of around 5% of the Portuguese demand. This dataset aggregates data of several types of consumers with some missing data (only 312 consumers in the period 2012-13 have consistent data) [6]. No information regarding individual appliances is available, therefore, flexible, and inflexible demands must be extrapolated.

2.5 The IDEAL Household Energy Dataset

Location: United Kingdom
Parameters available: Active and apparent power, room and boiler pipes temperatures, and individual appliances data.
Measurement period: 11/2016-06/2018
Temporal resolution: 1 sec, 5 sec
Type of aggregation (Building, house, etc.): House
Overall Quality: Some missing data and non-linearity
Link: https://datashare.ed.ac.uk/handle/10283/3647
Description: Power and temperature of 255 UK houses and the appliances data of 39 houses.

This dataset contains information about active and apparent power, and room and boiler pipes temperatures in 255 houses aggregated from Edinburgh, United Kingdom. The time series data varies from two months to two years in the period of 11/2016-06/2018 with a temporal resolution of 1 second [7]. It also contains a survey on social and economic aspects of houses. Furthermore, for 39 houses there is information about the individualized appliance level. Some missing data and non-linearity in time occur in this dataset. Therefore, extra effort must be expended to treat, clean, and understand the data.

2.6 REFIT: Electrical Load Measurements Dataset

Location: United Kingdom

Parameters available: Power consumption

Measurement period: 2013-2015

Temporal resolution: 8 sec

Type of aggregation (Building, house, etc.): House aggregated (20) with 9 appliances individualized

Overall Quality: Good - a cleaned dataset is available

Link: https://pureportal.strath.ac.uk/en/datasets/refit-electrical-load-measurements-cleaned

Description: Aggregate loads for 20 houses in the United Kingdom.

This dataset contains information regarding aggregate loads (in Watts) for 20 houses in the United Kingdom. In addition to the aggregated load for each house, 9 individual appliance measurements (fridge-freezer, washing machine, dishwasher, television, microwave, toaster, Hi-Fi, kettle, and overhead fan) are also available. This dataset has two years of data in the period between October 2013 and June 2015 with 8-second intervals per house. This version of the dataset only contains cleaned data. According to the authors, the objective of this dataset is to be used for research in demand response measures, non-intrusive appliance load monitoring, appliance usage analysis, etc.

2.7 Local Energy System Data: A South-Eastern Town in Spain

Location: El Realengo district, Crevillent, Spain

Parameters available: Power consumption/generation data, Operational parameters, Distribution network parameters

Measurement period: 2019, 2020

Temporal resolution: Hourly

Type of aggregation (Building, house, etc.): Supply point, Node

Overall Quality: Good

Description: A dataset from the small Spanish town and municipality Crevillent.

A local energy system that includes residential and commercial loads, battery energy storage systems and variable renewable energy sources is considered. For covering the data requirements of this case, time series and other parameters of an actual LES have been used. More specifically a LES that was conceived and developed in the context of the H2020 MERLON project in the Crevillent town and municipality that are in the Alicante province, on the south-east part of Spain [8], constitute an ideal source of data.

In that area, the energy cooperative Enercoop that has a long tradition in the energy sector and spans its activities vertically through the entire value chain [9], is active. The cooperative owns and operates generation and storage assets, as well as the local distribution network which services end users. The pilot site of the MERLON project in Crevillent, was in El Realengo district, an urban area of approximately 320 inhabitants that consists of a core of low height houses around a social public centre. The LES consisted of supply points connected in different nodes, PV plants as well as a Battery Energy Storage System (BESS), with the network being presented in Figure 1. Details about the pilot site and the LES, as well as its integration can be found in the project deliverables [8], [9].

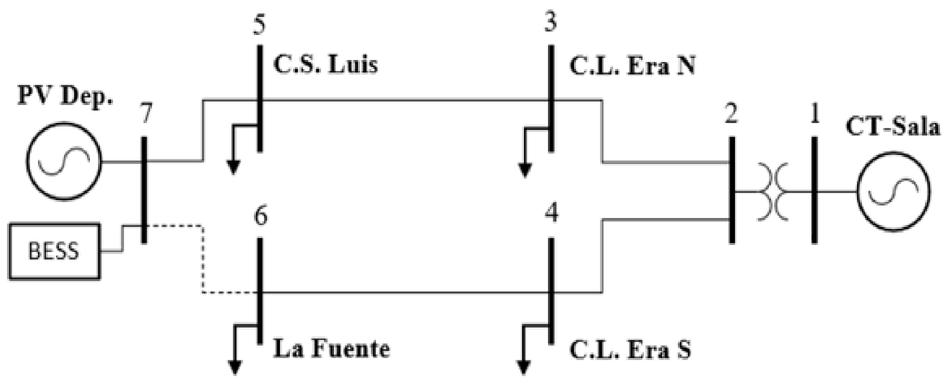


Figure 1: Single line diagram of the distribution network in El Realengo district, Crevillent.

Inspired by the pilot site LES in Crevillent, the new local energy system defined under the "South-Eastern Town in Spain" label, can be used as a testbed for the performance assessment of current and new market designs and trading mechanisms for Local Energy Communities.For that case the demanded load profiles, the PV generation profiles as well as the BESS operational parameters of the pilot site are used. Even though in this version of the deliverable there aren't any modelling needs for network representation, and a single node simplification has been made, this LES case offers the potential of incorporating the network parameters and enabling the representation of the network operation (power flows) if needed in the future. Given the TradeRES project orientation towards the presence of high shares of vRES in the energy mix, the LES case is extended by the incorporation of wind generation profiles from [10]. The resource utilised for the data needs of the other case studies of WP5 (e.g., national and pan-European level case studies) during the input database formation activities of WP2 has been also used here. Finally, for the BESS, although the operational parameters of the assets are considered are like those of the installation in El Realengo, the number of assets differs.

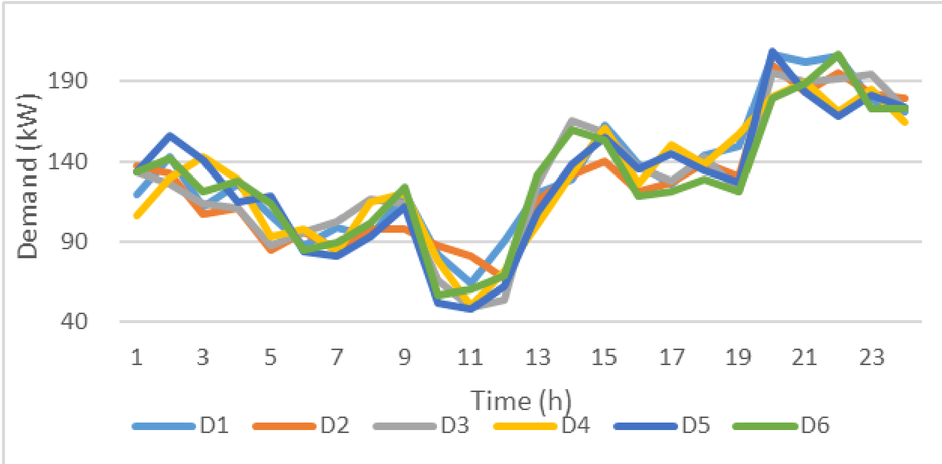


Figure 2: Demand of six building blocks in the constructed LES.

An example instance of the constructed LEC case is presented below. The hourly demand of six similar building blocks for one day has been constructed using the profiles of node 3 of six consecutive days commencing on April 1st, 2020. The demand timeseries, which have been rescaled uniformly for the constructed LES case, are presented Figure 2. Similarly, the generation profiles have been adjusted to present generation from vRES are shown in Figure 3. The constructed LES case is assumed to benefit from controllable micro-generation as well, with the number of assets being evenly distributed between the different technologies. The PV plants together with small-wind turbine systems although can classify as micro-generators are distinguished from other technologies such as the micro-combined heat & power (CHP) and biomass assets. In the micro-CHP case, electricity can be produced at a domestic level from gas, liquefied petroleum gas (LPG) or even hydrogen given their conversion capability, with heat being a by-product and the efficiency getting well improved compared to the independent systems. In the biomass case, power plants of medium/district level may provide a power generation in combination with district heating, which of course requires district heating network infrastructure that may not be economically viable in southern countries.

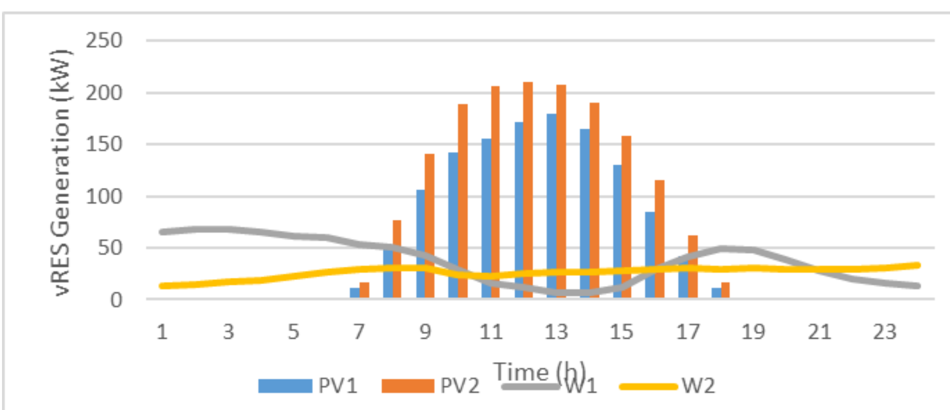


Figure 3: vRES generation in the constructed LES.

Beyond the demand and generated load timeseries, the wholesale energy prices of the period of interest are also considered among the data that form the constructed LES case. Figure 4 presents the price evolution of the day-ahead (DA) market for one day (April 1st, 2020). It should be stated that during the preparation of the first version of the deliverable there has been a significant rise in prices due to scarcity conditions in the gas market, which due to their temporal nature have not been taken into consideration.

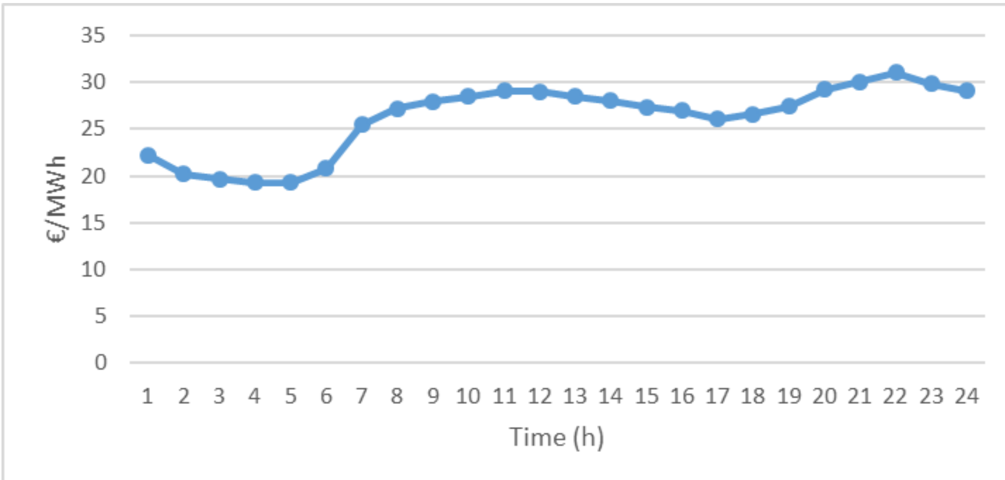


Figure 4: DA wholesale market price in Spain (April 1st, 2020).

2.8 Summary of available data

In Table 1 a summary of all aforementioned datasets presented is provided.

Table 1: Summary table for all datasets discussed in Section 2.

Name	***Description***	***Quality***	***Types of aggregation***	***Temporal resolution***	***Period***	***Parameters***	***Location***
UiS Energy Lab Apartments	Consumption and generation for six small apartments at the University of Stavanger campus.	Some missing data for one solar panel and wind turbine	Small apartments	5min, 15min, 1 hour	2019-2022	Power consumption, power generation, weather data	University of Stavanger, Norway
IEEE PES ISA Open Data Sets	A collection of open datasets from various regions and aggregation.	Some missing data and non-linearity	Houses, office buildings, commercial buildings, EVs, PV generation, Wind generation	5 sec, 10 sec, 1 min, 5 min, 15 min, 1 hour	2000-2009, 2011, - 2020	Power consumption, power generation, EV's state of charge, weather data	Portugal, Brazil, EU
Data from the Commission for Energy Regulation	Irish consumption data of 3000 houses during 2009-2019.	Good	Houses	30 min	2009-2010	Energy consumption data and survey answers	Ireland
Elergone Project, NORTE-07-0202-FEDER-038564	Aggregated consumption data of 370 medium voltage Portuguese consumers.	Good in 2012 and 2013	Medium tension aggregation	15 min	2011-2014	Power consumption	Portugal

Name	***Description***	***Quality***	***Types of aggregation***	***Temporal resolution***	***Period***	***Parameters***	***Location***
The IDEAL Household Energy Dataset	Power and temperature of 255 UK houses and the appliances data of 39 houses.	Some missing data and non-linearity	House	1 sec, 5 sec	11/2016-06/2018	Active and apparent power, room and boiler pipes temperatures, and individual appliances data.	United Kingdom
REFIT: Electrical Load Measurements Dataset	Aggregate loads for 20 houses in the United Kingdom.	Good - a cleaned dataset is available	House aggregated (20) with 9 appliances individualized	8 sec	2013-2015	Power consumption	United Kingdom
Crevillent – A southern town in Spain	A dataset from the small Spanish town and municipality Crevillent.	Good	Supply point, Node	1 hour	2019, 2020	Power consumption/generation data, Operational parameters, Distribution network parameters	El Realengo district, Crevillent, Spain

3. Methodologies

This section describes the methodologies that will be used to carry out the simulation and performance analysis for this task. Methods of performing transactions, and designing local energy markets, market players' behaviours and how they interact, and finally how such a system can be achieved using blockchain technology.

3.1 P2P Electricity Transactions Considering a Centralized Optimization

In this model, a central optimization considering a mixed-integer linear programming (MILP) formulation is developed. The approach considers the minimization of the total social welfare costs of the community considering the equation presented in (1).

$$minimize\colon \sum_{i=1}^{Ni}\sum_{t=1}^{Nt}\left(p_{t,i}^{buy\ grid} \times ToU_{t,i} - p_{t,i}^{sell\ grid} \times FiT_{t,i}\right) \times \frac{1}{\Delta t} + FixCost_i \tag{1}$$

where, $p_{t,i}^{buy\ grid}$ represents the power bought from grid, $ToU_{t,i}$ represents the time of use tariff paid to buy electricity from retailer, $p_{t,i}^{sell\ grid}$ represents the power sold to the grid, $FiT_{t,i}$ represents the value of feed-in tariff to sell electricity to the grid, Δt represents the scaling time factor, $FixCost_i$ represents the fixed costs paid by each player, Ni represents the total number of players and Nt represents the number of periods. Equation (2) presents the power balance of each player in each period.

$$p_{t,i}^{import} + p_{t,i}^{gen} + p_{t,i}^{dch} = p_{t,i}^{export} + p_{t,i}^{load} + p_{t,i}^{ch}, \forall t \in Nt, \forall i \in Ni \tag{2}$$

where, $p_{t,i}^{import}$ is the power imported by the player, $p_{t,i}^{gen}$ corresponds to the power generated, $p_{t,i}^{dch}$ corresponds to the battery discharge power, $p_{t,i}^{export}$ represents the power exported by player, $p_{t,i}^{load}$ corresponds to the power of load and $p_{t,i}^{ch}$ represents the battery charge power. Equation (3) calculates the total import power of a player.

$$p_{t,i}^{import} = p_{t,i}^{buy\ grid} + \sum_{j=1 \quad j\neq i}^{Nj} p_{t,i,j}^{buy\ P2P}, \forall t \in Nt, \forall i \in Ni \tag{3}$$

where, $p_{t,i,j}^{buy\ P2P}$ represents the power bought from peer-to-peer (P2P). Equation (4) gives the power exported by each player.

$$p_{t,i}^{export} = p_{t,i}^{sell\ grid} + \sum_{j=1 \quad j\neq i}^{Nj} p_{t,i,j}^{sell\ P2P}, \forall t \in Nt, \forall i \in Ni \tag{4}$$

where, $p_{t,i,j}^{sell\ P2P}$ represents the power sold from P2P. Equations (5) - (7) limit the maximum quantity of power bought and sold to the grid and the simultaneous actions.

$$p_{t,i}^{buy\ grid} \leq \overline{p_{t,i}^{buy\ grid}} \times X_{t,i}^{buy\ grid}, \forall t \in Nt, \forall i \in Ni \tag{5}$$

$$p_{t,i}^{sell\ grid} \leq \overline{p_{t,i}^{sell\ grid}} \times X_{t,i}^{sell\ grid}\ \forall t \in Nt, \forall i \in Ni \tag{6}$$

$$X_{t,i}^{buy\ grid} + X_{t,i}^{sell\ grid} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{7}$$

where, $\overline{p_{t,i}^{buy\ grid}}$ represents the maximum limit for buying power from the grid, $X_{t,i}^{buy\ grid}$ is the associated binary variable to the buy from grid action, $\overline{p_{t,i}^{sell\ grid}}$ is the maximum limit to sell electricity to the grid and $X_{t,i}^{sell\ grid}$ is a binary variable associated with the sell to grid option. Equations (8) - (10) limit the maximum quantity of power bought and sold in P2P, and the simultaneous actions.

$$p_{t,i,j}^{buy\ P2P} \leq \overline{p_{t,i,j}^{buy\ P2P}} \times X_{t,i,j}^{buy\ P2P}, \forall t \in Nt, \forall i \in Ni \tag{8}$$

$$p_{t,i,j}^{sell\ P2P} \leq \overline{p_{t,i,j}^{sell\ P2P}} \times X_{t,i,j}^{sell\ P2P}\ \forall t \in Nt, \forall i \in Ni \tag{9}$$

$$X_{t,i,j}^{buy\ P2P} + X_{t,i,j}^{sell\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{10}$$

where, $\overline{p_{t,i,j}^{buy\ P2P}}$ represents the maximum limit for buying electricity in P2P, $X_{t,i,j}^{buy\ P2P}$ represents the associated binary variable to the buy from P2P action, $\overline{p_{t,i,j}^{sell\ P2P}}$ represents the maximum limit for selling electricity in P2P, and $X_{t,i,j}^{sell\ P2P}$ represents the binary variable for the sell to P2P action. Equation (11) represents the energy balance of the P2P transactions.

$$\sum_{i=1\quad i\neq j}^{Ni} \sum_{j=1\quad j\neq i}^{Nj} p_{t,i,j}^{buy\ P2P} = \sum_{j=1\quad j\neq i}^{Nj} \sum_{i=1\quad i\neq j}^{Ni} p_{t,i,j}^{sell\ P2P}, \forall t \in Nt \tag{11}$$

Equations (12) and (13) present the conditions imposed to avoid simultaneous transactions in the grid and P2P mode.

$$X_{t,i}^{buy\ grid} + \sum_{j=1\quad j\neq i}^{Nj} X_{t,i,j}^{sell\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{12}$$

$$X_{t,i}^{sell\ grid} + \sum_{j=1\quad j\neq i}^{Nj} X_{t,i,j}^{buy\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{13}$$

Equations (14) - (16) present the maximum limits for charge and discharge.

$$p_{t,i}^{dch} \leq \overline{p_{t,i}^{dch}} \times X_{t,i}^{dch}, \forall t \in Nt, \forall i \in Ni \tag{14}$$

$$p_{t,i}^{ch} \leq \overline{p_{t,i}^{ch}} \times X_{t,i}^{ch}\ \forall t \in Nt, \forall i \in Ni \tag{15}$$

$$X_{t,i}^{dch} + X_{t,i}^{ch} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{16}$$

where, $\overline{p_{t,i}^{dch}}$ represents the maximum power of discharge, $X_{t,i}^{dch}$ is the binary variable associated with the battery discharge, $\overline{p_{t,i}^{ch}}$ represents the maximum power of charge, $X_{t,i}^{ch}$ is the binary variable associated to the battery charge. Equation (17) represents the batteries energy balance.

$$e_{t,i}^{bat} = e_{t-1,i}^{bat} + \left(p_{t,i}^{ch} - p_{t,i}^{dch}\right) \times \frac{1}{\Delta t}, \forall t \in \{2{:}Nt\}, \forall i \in Ni \tag{17}$$

where, $e_{t,i}^{bat}$ represents the energy state of a battery.

$$0 \leq p_{t,i}^{buy\ grid} \leq \overline{p_{t,i}^{buy\ grid}}, \forall t \in Nt, \forall i \in Ni \tag{18}$$

$$0 \leq p_{t,i}^{sell\ grid} \leq \overline{p_{t,i}^{sell\ grid}}\ \forall t \in Nt, \forall i \in Ni \tag{19}$$

$$0 \leq X_{t,i}^{buy\ grid} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{20}$$

$$0 \leq X_{t,i}^{sell\ grid} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{21}$$

$$0 \leq p_{t,i,j}^{buy\ P2P} \leq \overline{p_{t,i,j}^{buy\ P2P}}, \forall t \in Nt, \forall i \in Ni \tag{22}$$

$$0 \leq p_{t,i,j}^{sell\ P2P} \leq \overline{p_{t,i,j}^{sell\ P2P}}\ \forall t \in Nt, \forall i \in Ni \tag{23}$$

$$0 \leq X_{t,i,j}^{buy\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{24}$$

$$0 \leq X_{t,i,j}^{sell\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{25}$$

$$0 \leq p_{t,i}^{dch} \leq \overline{p_{t,i}^{dch}}, \forall t \in Nt, \forall i \in Ni \tag{26}$$

$$0 \leq p_{t,i}^{ch} \leq \overline{p_{t,i}^{ch}}\ \forall t \in Nt, \forall i \in Ni \tag{27}$$

$$0 \leq X_{t,i}^{dch} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{28}$$

$$0 \leq X_{t,i}^{ch} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{29}$$

$$\underline{e_{t,i}^{bat}} \leq e_{t,i}^{bat} \leq \overline{e_{t,i}^{bat}}, \forall t \in Nt, \forall i \in Ni \tag{30}$$

$$\left\{X_{t,i}^{buy\ grid}, X_{t,i}^{sell\ grid}, X_{t,i,j}^{buy\ P2P}, X_{t,i,j}^{sell\ P2P}, X_{t,i}^{dch}, X_{t,i}^{ch}\right\} \in \mathcal{Z} \tag{31}$$

$$\{t, i, j\} \in \mathcal{Z}_+ \tag{32}$$

where, $\overline{e_{t,i}^{bat}}$ and $\underline{e_{t,i}^{bat}}$ represent the maximum and minimum limits for the battery's states. Equation (31) defines the integer variable and equation (32) the integer positive indices.

3.2 Auction-Based Trading for Local Energy Communities

As discussed in [11], local electricity markets will play a crucial role in the decentralization of power and energy systems that will focus on consumers and/or prosumers, distributed micro generation, and energy efficiency [12, 13, 14, 15]. A growing interest in the study and development of local electricity markets has appeared in the recent years supported by new concepts as peer-to-peer energy trading [16, 17, 18], blockchains [19, 20], transactive energy [21, 22, 23], and demand response (DR) [24, 25] , among others. In the existing literature, several authors already addressed auction-based local electricity markets [22, 26, 27, 28]. A large variety of market schemes fall under the concept of "auction" being hard to properly describe what represents an auction. Across all common market models that are considered as auctions, the use of bids for buyers to report their willingness to pay, and the market's outcome is deduced solely from these reported values prevails [29].

The double auction is the most common trading design [22, 26] (symmetric), and the single-sided auction [27, 28] (asymmetric). In the case of symmetric market pools [30, 31], buyers and sellers participate by submitting their bids. In electricity markets, a bid consists of the pair: amount of energy to trade, and the respective price per unit. Bids from buyers are ordered by price in descending order. In the seller case, the bids are ordered in an ascending way. These bids form the demand and supply step curves. The point where both curves intersect (Figure 5a) defines the quantity of energy to trade, while the market price is set by the last seller to sell. Buyer bids offering prices higher than the market price and seller bids offering prices lower than the market price trade in the market pool. In the end, each buyer must pay the market price for each accepted supply unit.

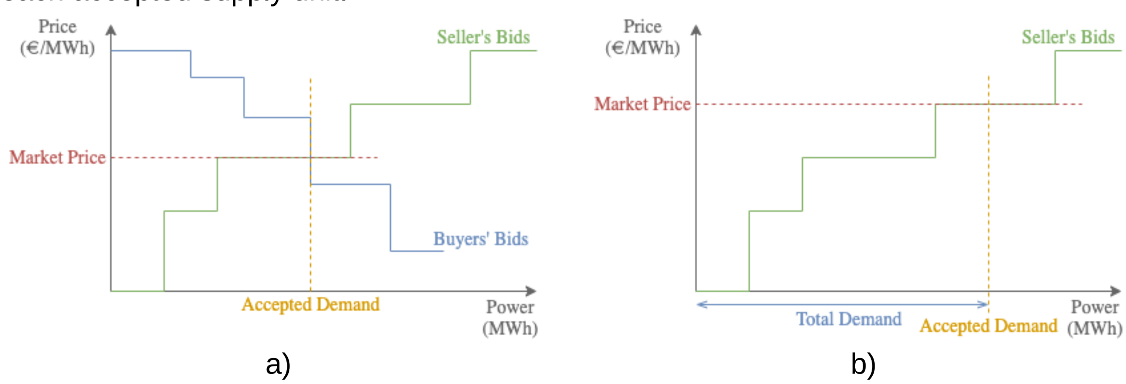


Figure 5. Usual auction-based electricity markets designs for: a) double auction or symmetric market pool; b) single-sided auction or asymmetric market pool [11].

In asymmetric market pools case, only sellers submit energy/price bids for the market, while buyers only submit their energy demand. The seller bids are ordered by price in ascending order. The sum of the buyers' necessary energy sets the total demand. Until the total demand is satisfied, the seller bids are accepted. The last seller to trade defines the market price that all buyers have to pay per each energy unit traded (Figure 5b).

3.3 Bi-level Modelling of Interactions at the Local Level

According to D3.2 local energy communities may take different market roles, with the prosumers being the most prominent. Business models for local energy systems and local energy communities are presented and analysed in [32]. To that extent, the prosumer actor that was analysed both with respect to the behavioural and operational dimension plays a key role at the local level. As presented in D4.4, the direct interaction of prosumers with the upper level of aggregation, e.g. suppliers and/or aggregators set the dynamics at the local level [33]. An alternative to this cross-layer integration is provided through the local market paradigm where the distributed resources are allowed to participate in mutually beneficial energy trading. This concept is presented in the schematic of Figure 6 that aimed to highlight the boundaries the local environment sets. Given the decentralised nature of the decision making around the operation of the distributed resources and the mobilization of flexibility through the price signals, the adoption of a bi-level programming framework is considered appropriate for the modelling of the interactions within the “Broad Local Environment” of Figure 6.

Although bi-level optimization refers to the nested form of multiple optimization problems, it has its grounds in game theory. The hierarchical problem described in a Stackelberg game, i.e., a competitive game of sequential game play, considered the leader to move first and the follower to react to the leader’s action. The asymmetry imposed by the hierarchical structure leads to the anticipation of the best response of the follower to the leader’s optimization problem. Therefore, the optimization problem of the leader (upper level) contains a nested optimization problem that corresponds to the follower’s problem (lower level), while there are coupling parameters and variables. A typical extension of the Stackelberg game is the bi-level optimization problem where the followers are many, leading to a single upper level (UL) and multiple lower level (LL) problems. This extension is suitable for modelling the interactions within the “Broad Local Environment”, where the supplier is the role of internalising the responses of its customers that can either be presuming entities, energy communities and markets.

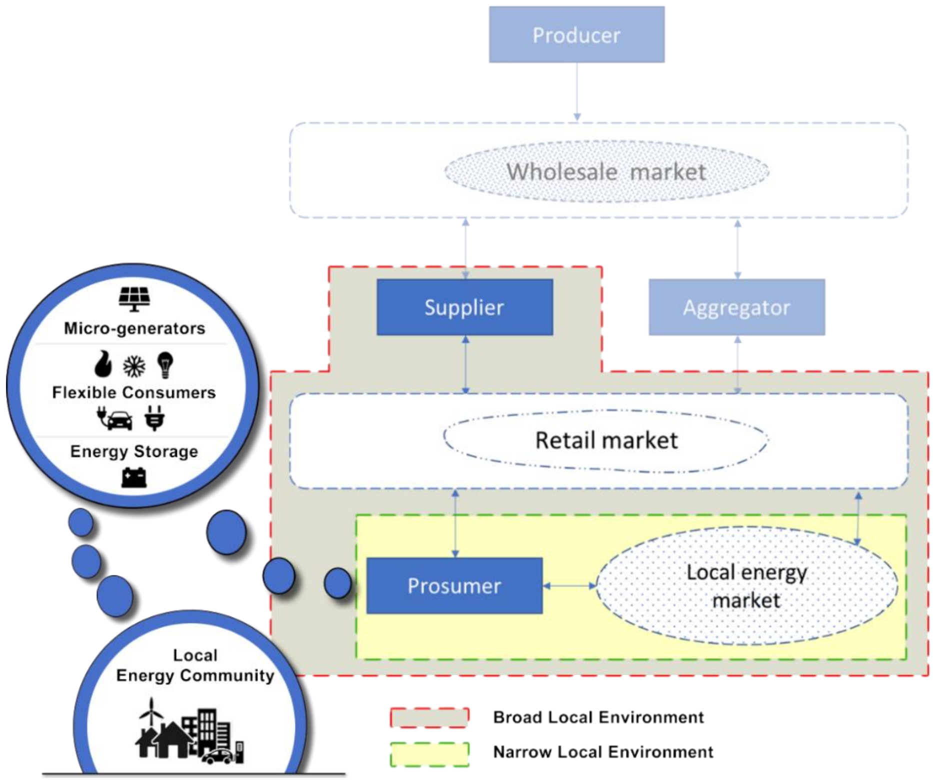


Figure 6: Areas of LEM Simulation Framework focus [33].

3.3.1. Formulation Overview

One key property of this key innovative modelling technique is the capturing of the supplier's strategic pricing decisions and the interplay between the supplier, the prosumers, and the Local Energy Market (LEM) that is formed from its client base. Given the time-spanning, the problem formulation defined as a multi-period bi-level optimization problem, with the generic and high-level overview being shown in Figure 7. The UL problem represents the strategic decision-making of a self-interested supplier who determines the optimal time-specific retail prices offered to customers for buying and selling energy. Following the findings of D3.2 [34], the main operational objective of the supplier has been profit maximization, while they must adhere to regulatory framework around the retail tariffs, which in terms of the model is translated to operational constraints. This problem at the UL is subject to the LL problems. The first three are related to the decision-making of three distinct instances of the prosumer actor, the flexible consumer (FC), the micro-generator (MG), and energy storage owner (ES). Such actors are assumed to also participate in the LEM, which sets the fourth LL problem that described the centralised operation of a LEM with different participants (FC, MG, and ES). Following the analysis conducted in D3.2, the individual presuming actors aim to optimise their demand/generation response to a given retail pricing scheme in order to maximise their own economic surplus [34]. Similarly, the LEM, given the offered retail prices and the techno-economic parameters of the participants' assets, derives the optimal dispatch and the energy exchanges with the retailer so that the total surplus is maximised.

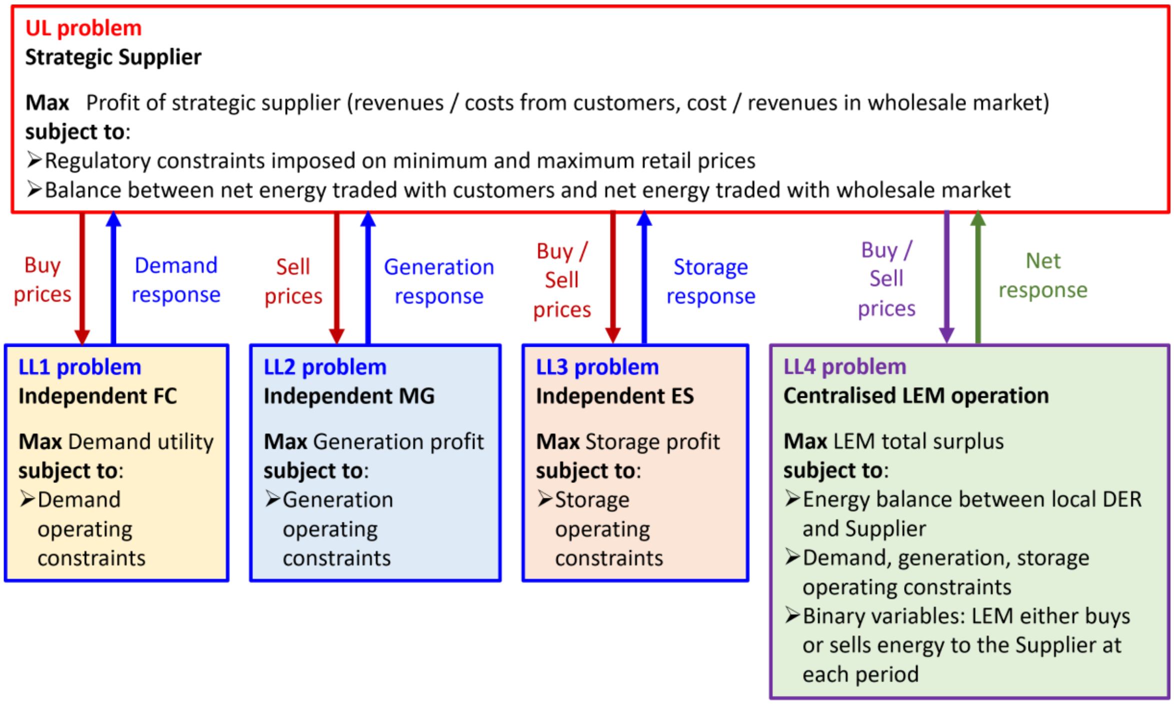


Figure 7: Schematic representation of bi-level optimization problem formulation.

3.3.2. Individual Optimization Problems

The UL problem consists of the optimization of the pricing decisions of the examined supplier, with the offered prices being differentiated with respect to the transaction type, i.e., to the prices for buying and selling energy respectively. The objective function of the supplier that is to be maximised, consists of the supplier's overall profits that result from the subtraction of the operational costs from the revenues.

The revenues originate from sales of energy to the end users, i.e., the independent consumers, the independent energy storage during the charging phase, and the LEM when buying energy from supplier (if applicable). On the other hand, the costs are the expenditures for buying energy from the generators, i.e., the independent micro-generators, the independent energy storage during discharging, and the LEM when selling energy to the supplier (if applicable). The economic transactions of the supplier with the wholesale market that correspond to the energy trading are finally complementing its profit function.

The operation of the supplier is limited by the regulation framework that is assumed to impose a cap on the retail prices, limiting the market power they may possess. Finally, the supplier as a mediating entity without ownership of resources, obeys a balance constraint related to its trading activities; this is on each period, the net energy traded with its customers (independent players) and the net energy traded with the wholesale market are balanced out. A detailed description of the supplier’s problem is available in D4.4 (Section 5.3.1, Equations 5.1-5.3) [33].

The LL problems that refer to the demand response of the independent FC in the retail prices offered by the supplier (LL1). Given that a player does not participate in the LEM, the utility (satisfaction) perceived from the consumption of the purchased energy sets the one term of the objective function that is maximised, while the other term refers to the cost of buying the energy, where the “buy” prices are used. The flexibility of the consumer is bounded within limits that set the deferable load levels. On the other hand, LL2 deals with the optimization of the response of the generation side. Given the “sell” prices, the independent microgenerator maximises the profit from selling the energy produced to the retailer. The generation is limited by the operational limits of the asset (e.g., generation capacity, capacity factors, etc). It should be stated that the generic description of the microgenerator allows the consideration of quadratic cost which is compatible to the diminishing returns that are applicable to thermal generators. This can be reduced for the representation of renewable resources where the operating cost can be bounded by the levelized cost of electricity (LCOE) of the corresponding technology. Similarly, the energy storage assets (e.g., BESS) that are represented by the independent energy storage owner that set the LL3. The objective function again consists of the operational profit, which is formed by the difference between the revenues that result from selling energy to the supplier when discharging and the costs of buying energy when charging. The constraints in that case include the intertemporal balance constraint, the energy storage limits, the charging/discharging ratings and efficiency as well as the energy neutrality condition (initial/final conditions). The problems LL1-LL3 are presented in detail in D4.4 (Section 5.3.2, Equations 5.4-5.13) [33].

Finally, the LEM market is represented by LL4, under the assumption of centralised operation, i.e., the operational decisions are made centrally based on full information and direct controllability of the distributed assets. This assumption is expected to lead to the most efficient outcome that constitute an optimal outcome and a benchmark for evaluating the decentralised market implementation. In terms of conceptualisation, an example of the centralised LEM operation envisaged in the analysis and represented in the LL4 problem formulation would require the prosumers to truthfully share their operational and behavioural characteristics with the LEM operator (role that can also be played by an energy community [33], [35]) and assign the control of the resources or strictly commit to the derived scheduling and respect the transactions performed. The objective function of LL4, as presented in Figure 7 includes the total surplus of the LEM, which is to be maximized. It consists of the total benefit of all the independent instances of the prosumer that participate in the local market, as well as the energy generation cost and the financial inflows/outflows that emerge during the transactions of the LEM with the supplier. A detailed formulation of LL4 is available in D4.4 (Section 5.3.3, Equations 5.28-5.37) [33].

3.3.3. Solution Outline

The generic case where all the LL problems coexist is used for deriving the analytical solution of the multi-period bi-level optimization problem. This corresponds to the case where independent FC, MG, and ES players (LL1-LL3) coexist with the LEM (LL4). These five optimization problems that have been presented in the previous section and in Figure 7 are grouped through the buy and sell prices, which are decision variables of the supplier (UL) that affect the responses of the customers/LEM (they are included in the objective functions of the LL1-LL4 problems). The other way around these responses of the customers/LEM affects the supplier's pricing decisions, as they are present in the objective function and the energy balance constraints supplier's formulation.

The case where there is not an LEM, all assets are independent and the problem is reduced to the UL optimization problem that is subject to the optimality of LL1-LL3 problems, is considered one of the two extreme cases. The other one is when all the distributed resources that have been internalised into the model, i.e., respond to the retail prices, participate to the LEM, so the UL optimization problem is subject to the optimality of LL4 problem. The conventional method for tackling a bi-level optimization problem is based on the conversion of the problem to a single-level mathematical problem with equilibrium constraints (MPEC) [36]. This is a constrained optimization problem that results in the substitution of the LL problems with their equivalent Karush-Kuhn-Tucker (KKT) optimality conditions, assuming the LL issues are continuous and convex, and presenting these conditions as constraints of the UL problem.

It should be noted that the LL4 problem is non-convex, as it includes the binary decision variables of the LEM to either buy or sell energy to the retailer at each period. Therefore, the generic bi-level optimization problem cannot be solved through the traditional approach of converting it to MPEC. The technique that is applied and outlined below is based on the relaxation and primal-dual reformulation of the non-convex LL problem and the penalization of the associated duality gap.

The flow chart of Figure 8 presents the relaxation and reformulation approach that enables the derivation of the analytical solution. The steps followed are based on [34] and summarised below:

- Problem LL4 is converted from a non-convex mixed integer problem to a convex problem by relaxing its binary constraints and making them continuous constraints. This is the constraint 5.30 from D4.4 replaced with $0 \le u\_t \le 1, \forall t \in T$.
- The dual problem associated with the relaxed LL4 problem is derived.
- A single-level optimization problem is formulated, and it is subject to the initial constraints of the UL problem, the derived KKT optimality conditions of the LL problems LL1-LL3, the primal and dual constraints of the relaxed LL4 problem and the binary constraints 5.30 appeared in the original LL4 problem. A term for penalizing the duality gap of the relaxed LL4 problem is also introduced in the objective function, to ensure optimality.
- The formulated problem contains the initial binary constraints and is thus non-linear. This is not linearized by applying the strong duality theorem and the binary expansion. The resulted problem is a mixed-integer quadratic program that can be solved to global optimality using commercial branch-and-cut solvers.

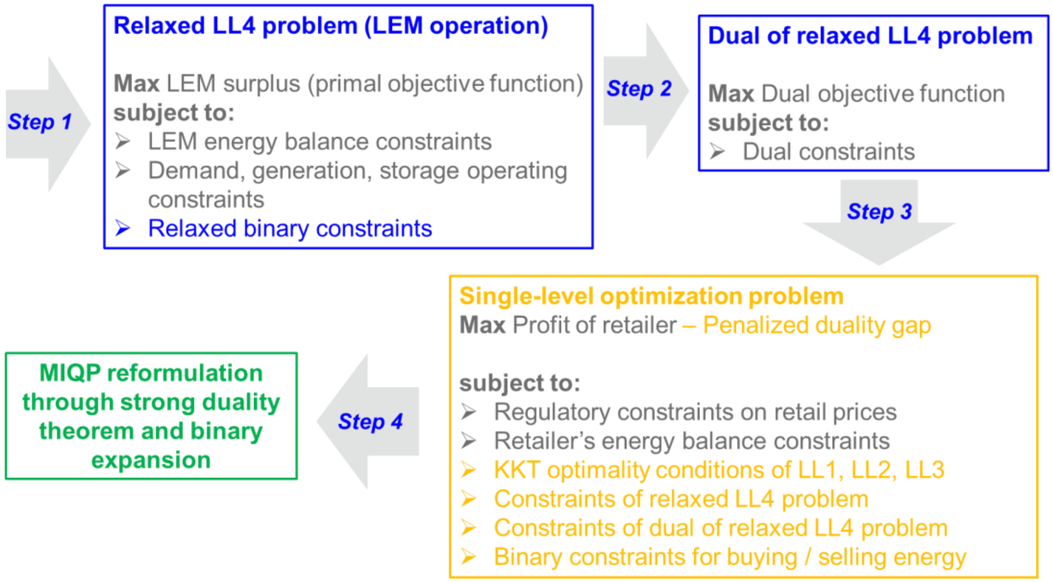


Figure 8: Relaxation and primal-dual reformulation of non-convex LL4 problem.

3.4 Blockchain Trading for Local Energy Communities

For actors in a market to trade between each other, there needs to be a system for executing and keeping track of transactions between all parties. Traditionally, this has been done using centralised services hosted by a broker. In contrast to this centralised system, a blockchain system is inherently decentralised. This means that transactions are executed and stored collectively by users or a consortium of trusted parties.

On a fundamental level, a blockchain is just a distributed ledger of all historical transactions and contracts, which are stored by a set of users. It can be configured in two ways; in a public blockchain where all users store a copy, or a private blockchain where the ledger is maintained by a consortium of trusted parties. These systems both ensure data integrity, decentralization, security, and redundancy. Another possibility unique to blockchain technology is the possibility of connecting it to a cryptocurrency blockchain such as Ethereum to facilitate trading directly between users. One option to make trading more intuitive for users is to allow trading with stable crypto currencies tied to local currency, such as Euro Coin [37].

Blockchains can also be used to store smart contracts between users, which can represent various agreements between two parties, such as a contract to buy power when the price is lower than a set threshold, or during a particular time frame, etc. This feature allows users to establish automated trading routines for energy within their local communities.

All transactions and smart contracts on the blockchain are available for anyone to see but cannot be changed by anyone. Because of this, it is possible to build websites and other services for easier management of the energy trading process. One example of such a service would be the use of artificial intelligence to buy and sell energy on behalf of the users to maximize profit based on usage behaviours.

For this deliverable, we propose a demo website for trading energy using blockchain technology in the backend. This website will use the data from Section 2 to create a realistic market environment in which the user can participate as a consumer or prosumer. This will consist of a web interface that shows data from one of previously discussed datasets. From here, the user should be able to participate in the market by either trading directly with the actors from the dataset, or by defining smart contracts to do this automatically once certain criteria are met. The user can then see a list of their transactions and try to minimize their electricity cost by buying and selling energy.

3.5 Conceptual LEC Approach based on aggregation of consumers and prosumers

In addition to the previous concepts, LNEG is also working on a conceptual LEC approach that is presented in this subsection and the results will produce for the second version of deliverable 5.2. The current stage of development of the methodology proposed by the LNEG within the scope of LECs, focuses on the aggregation of local consumers and prosumers as part of a local citizen energy community [38]. The community is managed by an aggregator who communicates with the members of the community and with the market operator. Further work may also consider local distributed generation and storage as part of the community [39].

3.5.1. Market Players' Behaviours

The *aggregator* has the main function of managing the local resources of the LEC to achieve its main goal of minimizing/maximizing its costs/revenues with energy [40]. Under this approach, the aggregator agent uses the input data (the day-ahead price, consumption, and production forecasts), and an optimization model with an objective function to achieve its goals. The aggregator communicates the expected price of energy in the day-ahead market to each LEC member and receives information regarding the inflexible and flexible loads. In the case of prosumers, the information sent to the aggregator is the net load (consumption minus the energy produced). The LEC aggregator signs contracts with its members considering real-time pricing tariffs without any markup (return over market prices).

Consumers and *prosumers* have information about some of the electrical equipment, generation, and storage assets. Their main functions consist in providing their inflexible and flexible net loads before the closure of the day-ahead market and their expected net load before the closure of the intraday market to the aggregator. These players are equipped with an optimization model that minimizes/maximizes their expected costs/revenues with energy according to the expected cost of energy in the day-ahead market and their daily expected consumption. Furthermore, they are also equipped with an optimization model that maximizes their utility function according to the market prices, their consumption behaviour, and their flexibility preferences.

The *market operator* has the main function of clearing the markets and computing the cost of the imbalance settlement. This market player receives bids (prices and quantities) from the aggregator and informs it regarding the market clearing (prices and power dispatch). In case of energy imbalances concerning the programmed dispatch of the aggregator, the market operator informs the aggregator about the penalties it must pay.

3.5.2. Detailed Communication Protocol and Interactions Between Market Players

Figure 9 presents the communication protocol between the different market players.

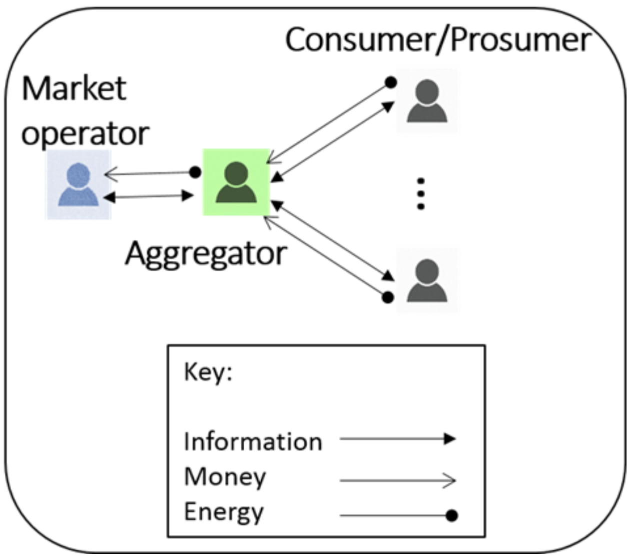


Figure 9: Communication protocol between players and the different interactions between the aggregator and the market operator.

The aggregator and the market operator communicate using a bilateral protocol. The aggregator submits bids to the different markets and receives information about the market prices and its programmed dispatch. Furthermore, in case of any deviations concerning the aggregator programmed dispatch, the market operator will inform the aggregator about the cost/revenue it has to receive because of those deviations. Figure 10 presents the interactions between the aggregator and the market operator.

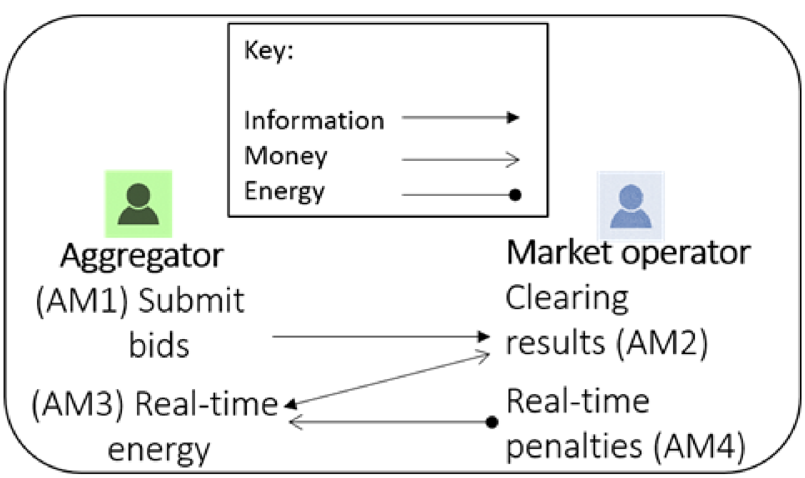


Figure 10: Interactions between the aggregator and the market operator.

The aggregator communicates with the members of the LEC using the contract net protocol, which means that it can communicate with all members, but the members cannot communicate with each other [16].

Figure 11 presents the communication interactions between the LEC aggregator and each of its members, such as the methodologies that will be used to provide the information needed in these interactions.

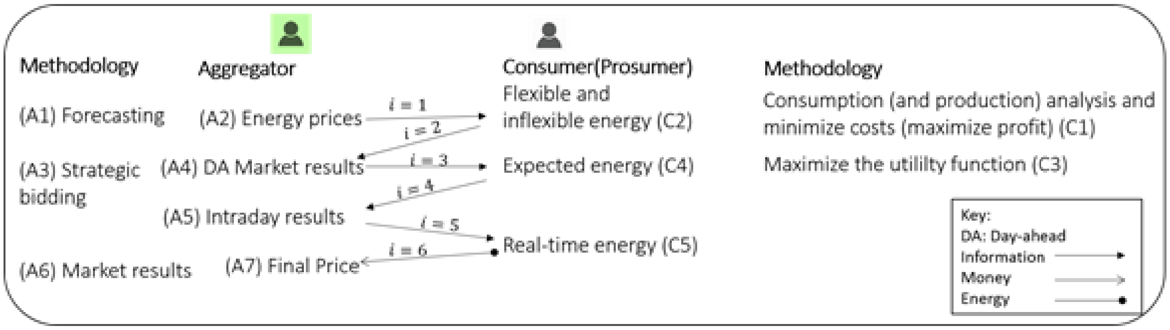


Figure 11: Interactions between the LEC aggregator and its members, and their methodologies.

This figure presents a protocol with six interactions, *i*, between the aggregator and its members. The aggregator starts by computing the expected prices of the day-ahead market, using a forecast methodology (A1). Then, it sends the prices to the members (A2).

Each member computes their flexible and inflexible net load according to an analysis of their expected net load and equipment preferences and flexibility, using an objective function that minimizes costs (or that maximizes revenues). According to their preferences concerning the usage of their electrical appliances, the optimization model computes all possible solutions to change their expected consumption, obtaining their flexible and inflexible net load (C1), and sending this information to the aggregator (C2). The aggregator receives these values and computes aggregated bids to the day-ahead market that minimizes/maximizes the costs/revenues of the LEC (A3), sending them to the market operator (AM1), who will reply with the market results (AM2).

The aggregator will inform the LEC's members about the market prices and the programmed dispatch of each one, waiting for their response with the expected final dispatch (A4). Then, each member computes its expected net load according to the maximization of a utility function (C3), which considers both consumption comfort and energy costs, sending it to the aggregator (C4). The aggregator receives the final expected dispatch of its members and using a strategic bidding algorithm (A3) submits the bids to the intraday market (AM1), receives the market results from the market operator (AM2). Then, each consumer receives information regarding its final programmed dispatch (A5). In this conceptual approach members are aware that if they do not comply with the expected final dispatch, they must pay penalties – different scenarios will be tested for this penalization.

The market operator verifies if the aggregator complies with the final dispatch (AM3), computing the imbalance prices otherwise (AM4). In case of deviations (C5), the aggregator will verify the members responsible for them (A6) and charge them (A7).

4. Case Studies

The aim of the presented case studies lies in analysing the techno-economic outcomes at the local level. Structural components related to market design considerations (e.g., structure of retail tariffs, local energy trading, flexibility procurement mechanisms) affect the interactions between the prosumers, the communities, and the aggregating entities. The effects that arise from the introduction of local trading as well as the efficiency and facilitation of the market mechanisms are the main aim of the conducted analysis. The case studies were selected based on the available datasets and what we will be able to implement within by the end of the deliverable.

4.1 P2G Case (Retail/Prosumer Interaction)

The peer-to-grid (P2G) case refers to a simplification of the conventional market structure where the prosumers are contracted with the single supplier that is assumed active in the area, for trading electricity according to predefined tariffs, i.e., prices for buying the energy deficit and Feed-in-Tariff (FiT) for selling the energy surplus. Examples of tariff structures vary from flat and the seasonal rates, to the real-time pricing schemes, with the Time-of-Use (ToU) and the dynamic tariffs also being indicative structures.

The interest of the analysis performed is limited to some of the structures such as the flat tariffs, the ToU tariffs and a simple version of dynamic tariffs. In contrast to the traditionally fixed prices, where the offered retail prices for importing or exporting energy from a supply point are flat throughout the examined daily horizon, the ToU pricing regimes set prices for certain intervals of this horizon (e.g., peak and off-peak periods) while the simple version of dynamic tariffs enables the buy and sell prices to be hourly specific.

It should be noted that this case constitutes the reference scenario, as it is assumed that there is not any local trading mechanism established, and that all the end-users interact individually with the supplier. Therefore, several metrics are presented at the end of each following subsection for enabling comparability between the cases considered in terms of social welfare. Regarding the methodology described in Section 3.3, the reference scenario corresponds to the one extreme instance of the multi-period bi-level optimization model (see Section 3.3.3) where the UL problem is subject to the optimality conditions of only the LL1-LL3. In terms of data, for this case study the constructed LEC case described in Section 2.7 has been used.

4.1.1. Simple Version of Dynamic Tariffs

In this version of the P2G case the decision variables related to the buy and sell retail prices can differ each time step and be affected by the demand and generation conditions of each hour. The overall demand that is served by the supplier, i.e., the realised demand that results as a response to the buy prices is shown in Figure 12. This is the demand of flexible consumers D1-D6 and has been reduced compared to the maximum levels because of the price elasticity assumed. The maximum levels of flexible consumers D1-D6 have been related to the profiles of blocks of buildings that were presented in Section 2.7. Similarly, the overall local energy generation is shown in Figure 12 and includes the six micro-generators modelled in the LL2 problem. The types of the micro-generators, as well as the required time series, have been considered in accordance with the example instance of Section 2.7.

Figure 13 shows the buy and sell prices at the Nash equilibrium. These are presented in contrast to the exogenous wholesale energy prices. It should be mentioned that the energy storage assets, in the P2G case, face the option of charging at the buy price and discharging at the sell price. The resulted buy-sell spread swifts the buy price curve at a totally higher level than the sell price curve, prohibits the ES from operating.

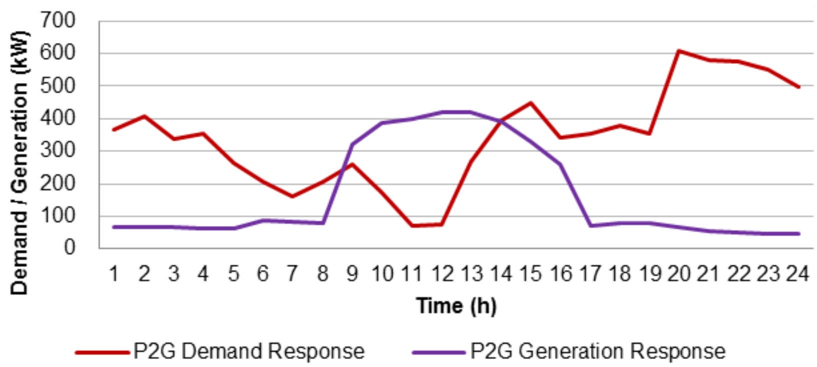


Figure 12: Demand and generation response for the P2G Case - Dynamic Tariff.

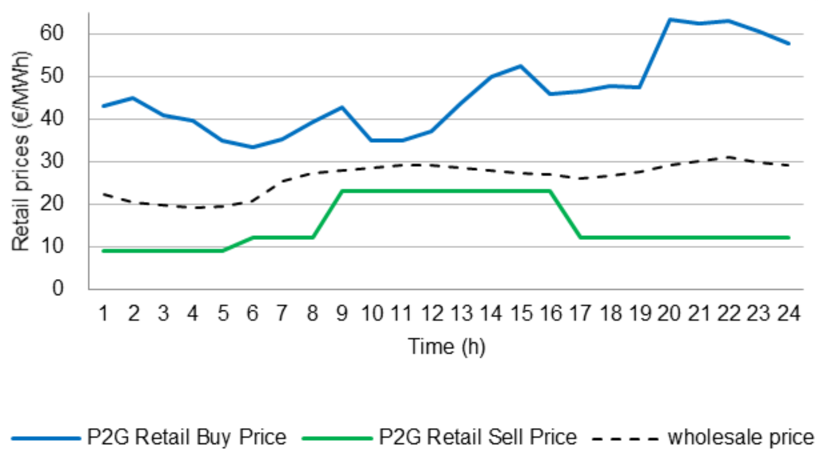


Figure 13: Buy and sell retail prices offered by the supplier in the P2G Case - Dynamic Tariff.

Relevant to the observation around the inactivity of the energy storage asset are two remarks. Firstly, is the sensitivity of the ES business case on the form of prices and their variability within the day. Moreover, the current version of the model, where different resources are assumed to be owned and operated from different entities, does not capture maximization of the self-consumption option, where storage could play an important role.

The self-consumption mode of the operation is very much in line with the local energy community concept and would require the integrated consideration of vRES generation and BESS.

In terms of modelling implementation this would either require the alteration of the ES sub-model (LL3) or the introduction of another independent player that would combine the behavioral and operational characteristics of both asset types.

The revenues for the supplier in that case turn out to be around €409.00, and the profits have been found to be €220.85. The utility of the FCs is found to be €99.97, and the profit of MGs €5.80, leading to an overall social welfare of €105.77 for the local stakeholders.

4.1.2. ToU and Flat Tariffs

This variation of the P2G case refers to the adoption of a ToU structure of the retail tariff that is applied to the retail buy prices. The two blocks distinguish between the hours of 23-12, which are considered off-peak hours, and the hours between 13-23 that are assumed to be the peak hours. The retail sell prices are assumed to be flat. Figure 14 shows the demand and generation response of the supplier's served customers. Figure 15 shows the buy and sell prices at the Nash equilibrium, as well as the exogenous wholesale energy prices.

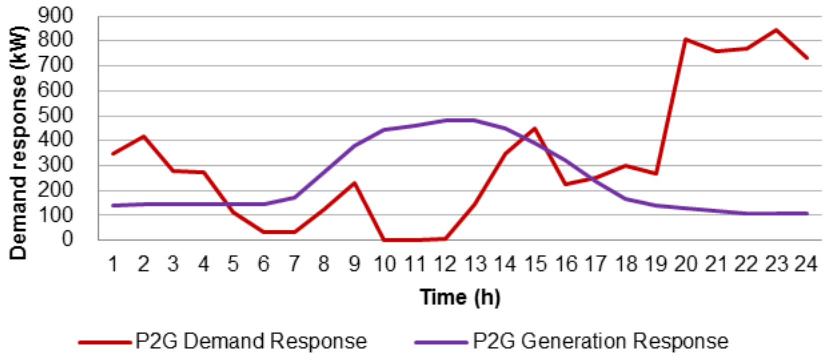


Figure 14: Demand and generation response for the P2G Case - ToU Tariff.

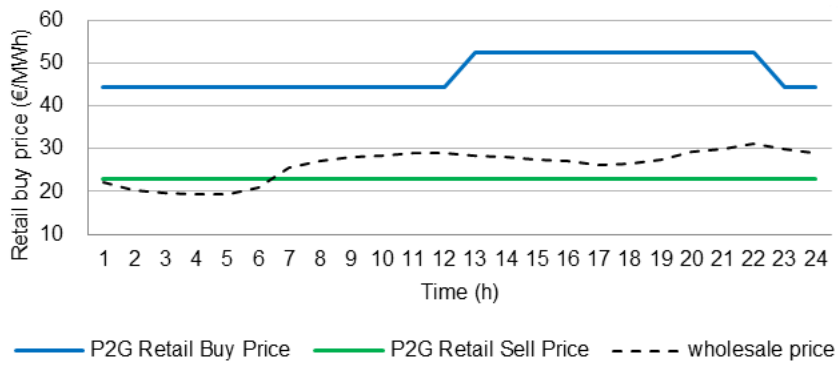


Figure 15: Buy and sell retails prices offered by the supplier in the P2G Case - ToU Tariff.

Since the ToU exhibits less flexibility with respect to the dynamic prices from Section 4.1.2, the strategic supplier has less ability to attract the energy consumptions of FC, resulting in a reduction of customer's' demand response (Figure 14). However, the customers' generation response increases when observing a more profitable sell price profile (the sell prices of early morning and evening in Figure 14 are higher than those in Figure 12). Given the assumptions made, the less flexible ToU buy prices and flat sell prices reduce the customer's demand response but increase the customers' generation response. The revenues for the supplier in this case have decreased to €378.20, and the profits to €189.63. The utility of the FCs has increased to €123.51, and the profit of MGs to €22.99, leading to an increased social welfare of €146.50 for the local stakeholders.

4.2 Centralised LEM (Retailer/LEM Interaction)

The centralised LEM case study corresponds to the other extreme instance of the multi-period bi-level optimization model described in Section 3.3.3. In that case the UL problem is subject to the optimality conditions of only the LL4, the constrained optimization problem that corresponds to the centralised operation of the LEM. All the customers that were previously independently and solely contracted with the supplier are now participating in the LEM. This means that the clearing at the local level results a favourable price for both parties that participate in the trade, with the bid-ask spread assumed to be zero (in reality the spread may not be negligible). The data used are the same as for the P2G case and related to the constructed LEC case described in Section 2.7.

4.2.1. Simple Version of Dynamic Tariffs

This is the case where the buy and sell retail prices can differ on each time step and be affected by the demand and generation conditions of each hour as well as the volume cleared within the LEM.

4.2.1.1. Demand, Generation, and Storage Response

For both scenarios, Figure 16 and Figure 17 illustrate the hourly profiles of the occurred overall demand and generation of customers that are served by the supplier. The resulting hourly profiles of the net demand of the LEM are shown in Figure 18 with the P2G case where no LEM being established to be trivial but presented for the purpose of comparison. It is important to highlight that during specific times before noon there is excess generation in the LEM, i.e., the net demand of the LEM is negative, while all the other hours there is deficit.

In the demand and generation response figures (Figure 16 and Figure 17), it can be observed that both the realised demand and the total generation served by the supplier exhibit the highest values across most of the hours in the P2G reference scenario. This is explained by the market power [41] of the retailer, who is operating under monopoly/monopsony conditions. This is because of the absence of an LEM, the independent end-users (FC, MG, ES) can only buy and sell energy through the supplier. On the contrary, with the centralised LEM in place, the customers have the option to trade energy bilaterally in more favourable terms with only the energy that exceeds the local balance to be exchanged with the supplier.

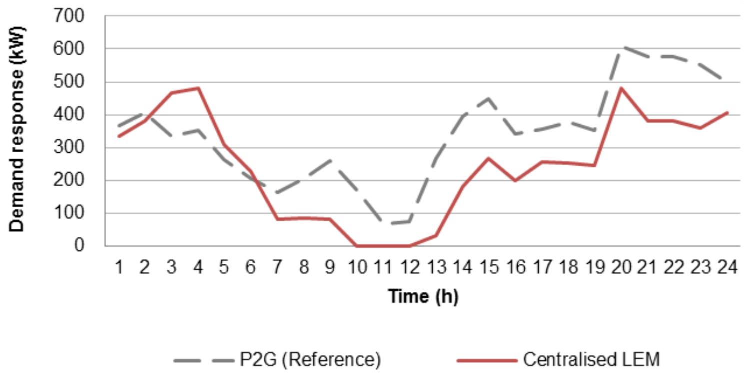


Figure 16: Total demand served by the supplier for two scenarios.

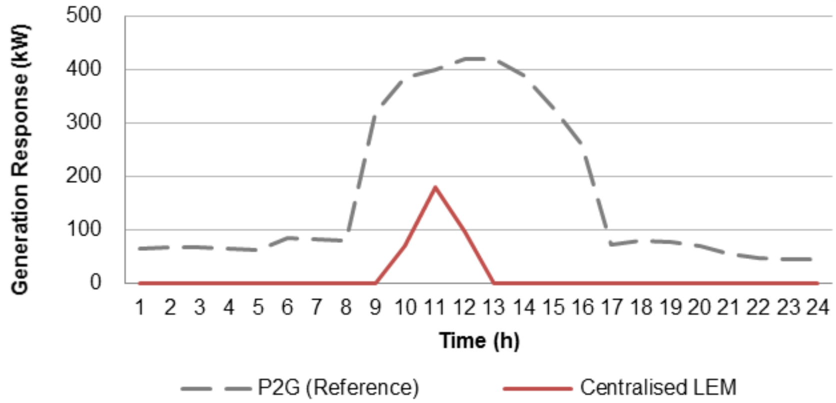


Figure 17: Total generation served by the supplier for two scenarios.

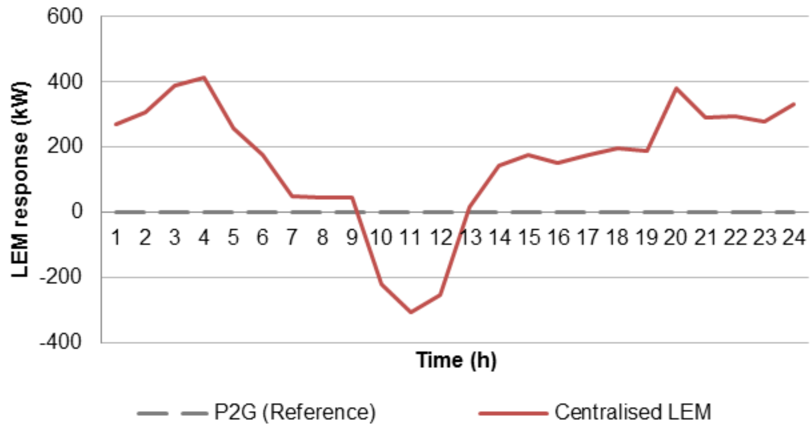


Figure 18: Net demand of LEM for two scenarios.

Therefore, although the dependency of the LEM participants on the supplier exists, it is limited since corresponds to different marginal evaluation levels. The LEM still buys energy from the supplier most of the day, with the exception being only the hours where there is excess generation and sells energy to the supplier during hours when the generation is higher than the low demand requirements.

Figure 19 presents the aggregated hourly charging / discharging power actions of the two ES players, with the charging and discharging being represented by positive and negative values respectively. It should be stressed that in the centralised LEM scenario, in contrast to the P2G reference scenario, the ESs participate in the LEM, and do not remain idle. ES undertakes charging / discharging actions, since it is beneficial for both the ES players and the counterparties that participate in the LEM and represent the generation and demanded load resources. Given that the participation in the local market leads to accessing the favourable LEM clearing price, which in contrast to the supplier's differentiated buy and sell prices presents zero spread, the energy arbitrage is made possible between the peak and the off-peak hours. Moreover, the LEM operates in a unified way, with the controllability over all the assets and the utilization of the aggregated flexibility to become a competitive advantage that limits further the dependency on the supplier.

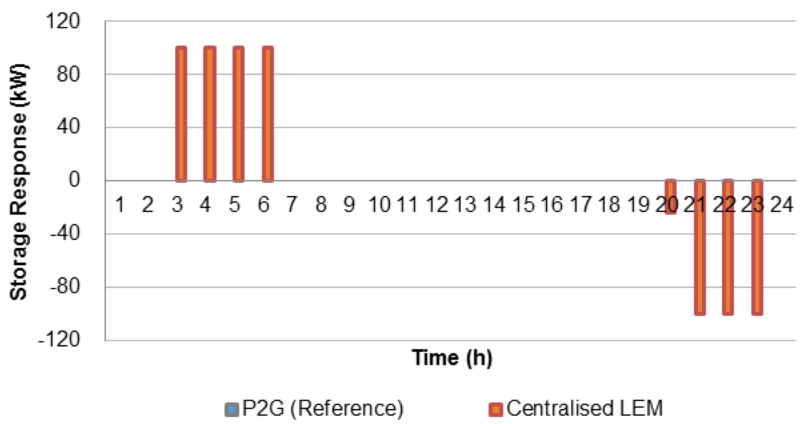


Figure 19: Aggregate charging / discharging power of ESs for two scenarios.

4.2.1.2. Retail Buy, Retail Sell, and LEM Prices

As far as the economic side of the interaction is concerned, there are three prices defined in the centralised LEM case. The LEM clearing price, the retail buy price, and the retail sell price. It should be noted that the fundamental definition of the price is based on the monetary value agreed upon for a realised transaction. In other words, the price is only well defined in the cases the bid and ask sides reach agreement (e.g., clearing) and the trade takes place. In Figure 20 and Figure 21 the hourly profiles of the retail buy price and retail sell price offered by the supplier for both P2G reference and centralised LEM scenarios are presented. For comparability purposes the wholesale prices that are faced by the supplier on its internal operation are also shown. It can be observed that for the centralised LEM case the retail buy price is not defined for the periods where there are no buy transactions with a supplier (Figure 20) price and respectively sell prices are only defined during times the LEM sells to the supplier (Figure 21).

Figure 22 illustrates the hourly profiles of the clearing prices of the LEM, which correspond to the dual variables of constraints of 5.29 from D4.4 (balance constraint of the LEM) together with the buy and sell prices offered by the supplier in the P2G reference scenario.

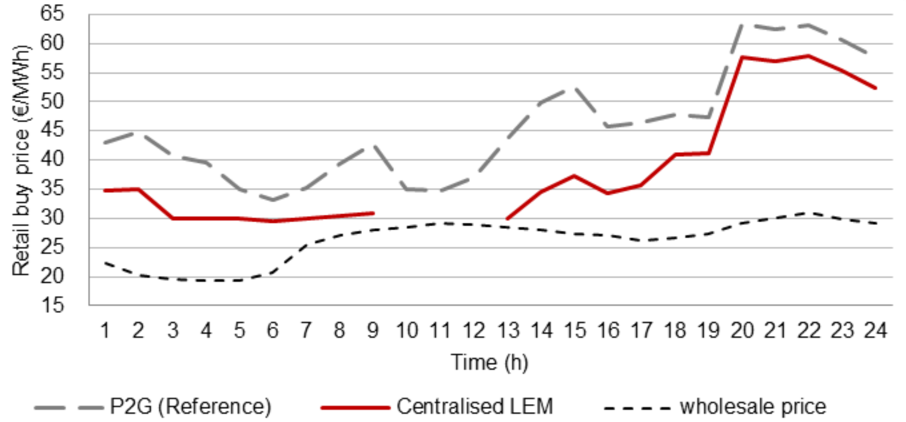


Figure 20: Buy prices offered by the supplier for two scenarios.

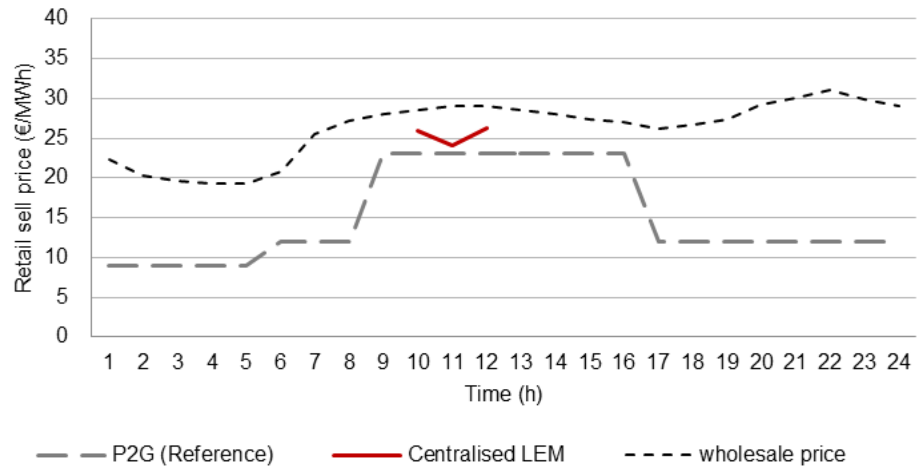


Figure 21: Sell prices offered by the supplier for two scenarios.

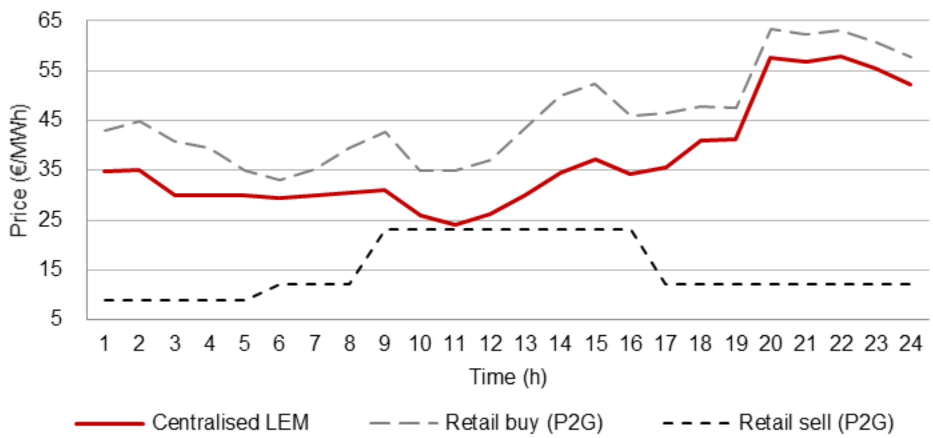


Figure 22: LEM clearing prices for two scenarios.

It can be observed from Figure 20 and Figure 21 that the strategic supplier in the P2G reference scenario offers very high buy prices (price level is much higher than the wholesale price) to demanding customers (Figure 20) and very low sell prices (price level is much lower than the wholesale price) to generating customers (Figure 21), trying to exploit the dependency of its served customers. These large differentials between buy and sell prices, constitute excursion of market power, and support the objective of the supplier for maximizing its overall operational profits.

In the centralised LEM scenario, when the LEM is introduced the participants in the market (all the end-users) choose to trade energy locally at the LEM prices (Figure 22). Given the high buy prices and low sell prices of the supplier, trading locally becomes mutually beneficial for all FC, MG, and ES participants. The effect of the limited dependency to the supplier, i.e. the total demand and the total generation served by the supplier are significantly reduced, is the reduction of the offered buy prices across the majority of hours 1-9 & 13-24 (Figure 20) in order to attract higher demand and compensate the reduction of its served demand caused by the LEM. Similarly, the supplier increases the offered sell prices substantially across hours 10-12 (Figure 21) to attract more generation and compensate the reduction of its served generation caused by the LEM.

Considering the supplier's business case, the effects arising from the introduction of the LEM show the limiting of the supplier's strategic potential. The above trends the exploitation of the customers through the large differentials between buy and sell prices is limited, bringing the offered buy and sell prices closer to the wholesale level. The consideration of the competition at the supplier's level would suppress prices further towards the wholesale values. Finally, the issue of the undefined prices could be resolved by considering the generic case, where some of the end-users participate in the LEM, while others only stay in business with the supplier, a set-up of the case study that could guarantee buy/sell transactions throughout the horizon.

4.2.1.3. Supplier's and Customers' Economics

The next step is to quantify and analyse the impact of LEM on the economics of the supplier and its served consumers. Table 2 presents the daily revenue, retail cost, wholesale net cost, and profit of the studied supplier.

Table 2: Economics of supplier for the two scenarios.

Scenario	Revenue (€)	Retail cost (€)	Wholesale net cost (€)	Profit (€)
P2G Reference	409.00	79.21	108.94	220.85
Centralised LEM	242.91	8.75	139.51	94.64

As seen in Table 2, the supplier's revenue represents the largest portion of its net profit, so we begin our examination there. Specifically, the centralised LEM scenario significantly reduces this retail revenue (68% with respect to the P2G Reference scenario). This tendency is caused by the fact that the introduction of the LEM decreases the supplier's buy prices (Figure 20), as well as the overall demand it serves (Figure 16). In a similar line, the centralised LEM scenario significantly lowers the supplier's cost of purchasing energy from its generating customers (805% with respect to the P2G Reference scenario). This tendency is caused by the fact that the LEM, despite a relatively slight rise in the sell prices (Figure 21), dramatically reduces the total generation served by the supplier (Figure 17).

Further, the centralised LEM scenario results in an increase of the supplier's net cost in the wholesale market (22% with respect to the P2G Reference scenario). The introduction of the LEM reduces the total generation served by the supplier more than the reduction of the total demand served by the supplier, which is what is causing this trend (Figure 16 and Figure 17). The supplier must therefore purchase more energy on the wholesale market. Overall, the introduction of the LEM significantly lowers the supplier's total profit in the centralized LEM scenario (133% in comparison to the P2G Reference scenario), which is principally caused by a decline in retail net revenue and a corresponding rise in wholesale net cost.

Moving our focus to the customers, Table 3 present the total (daily) economic surplus of FC, MG, and ES, as well as the customers' total social welfare. The economics of all the customer types (and social welfare) are increased in the centralised LEM scenario with respect to the P2G Reference scenario, since they trade energy based on the LEM clearing prices rather than the high retail buy prices and the low retail sell prices.

Table 3: Utility of flexible consumers for different scenarios.

Scenario	Utility of FC (€)	Profit of MG (€)	Profit of ES (€)	Social Welfare (€)
P2G Reference	99.97	5.80	-	105.77
Centralised LEM	187.88	86.27	6.46	280.61

4.2.2. ToU and Flat Tariffs

This variation of the centralised case refers to the adoption of a ToU structure of the retail tariff that is applied to the retail buy prices and a flat structure of the FiT that is applied to the retail sell prices. Specifically, the ToU is made up by two blocks distinguishing between the hours of 23-12 that are considered off-peak hours, and the hours between 13-23 that are assumed to be the peak hours. The FiT is assumed to be flat over the day.

4.2.2.1. Demand, Generation, and Storage Response

For both scenarios, Figure 23 and Figure 24 illustrate the hourly profiles of the occurred overall demand and generation of customers that are served by the supplier. The resulting hourly profiles of the net demand of the LEM are shown in Figure 25, with the P2G case where no LEM being established to be trivial but presented for the purpose of comparison.

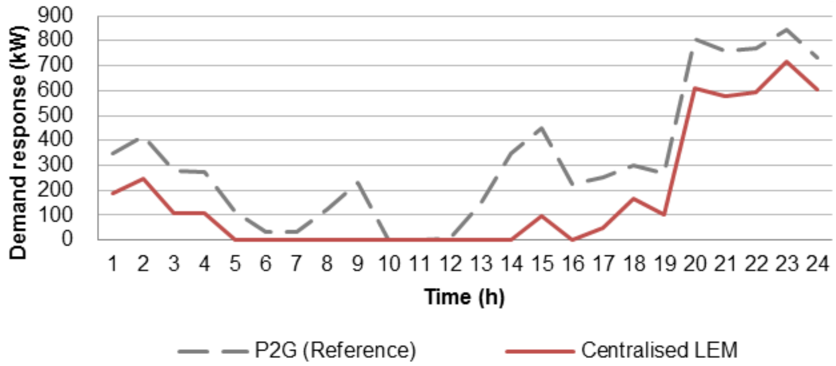


Figure 23: Total demand served by the supplier for two scenarios under ToU and flat tariffs.

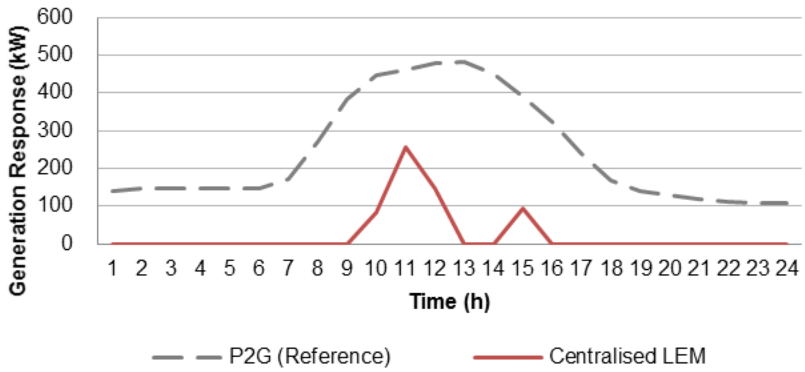


Figure 24: Total generation served by the supplier for two scenarios under ToU and flat tariffs.

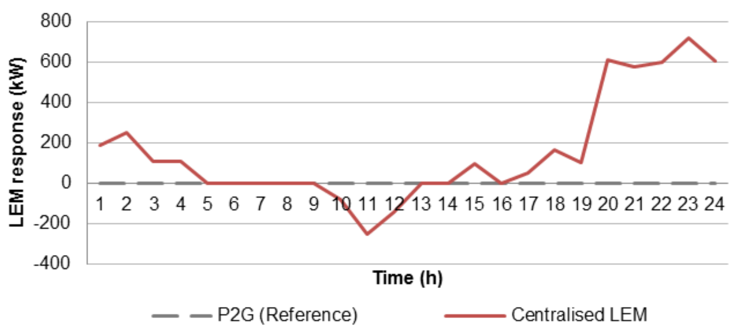


Figure 25: Net demand of LEM for two scenarios under ToU and flat tariffs.

It can be seen from the demand and generation response figures (Figure 23 and Figure 24), the realised demand and the total generation served by the supplier exhibit the higher values over the day in the P2G reference scenario compared to the centralised scenario. This is explained by the retailer's market power [41] in the market, which results from its monopoly/monopsony operations. This is because of the absence of an LEM, the independent end-users (FC, MG, ES) can only buy and sell energy through the supplier. Instead, with the centralised LEM in place, customers have the option to trade energy bilaterally in more favourable terms, exchanging only the energy that exceeds the local balance with the supplier. Figure 26 presents the aggregated hourly charging / discharging power actions of the two ES players, with the charging and discharging being represented by positive and negative values respectively.

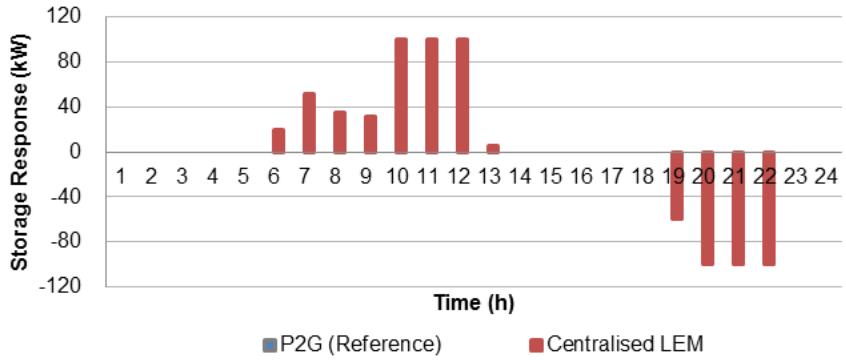


Figure 26: Aggregated charging/discharging power of ESs for scenarios ToU and flat tariffs.

It should be emphasized that, in contrast to the P2G reference scenario, the ESs actively participate in the LEM and behave charging / discharging actions in the centralised LEM scenario. Since it benefits both the ES players as well as the counterparties who participate in the LEM and represent the generation and demanded load resources. Given that the participation in the local market leads to accessing the favourable LEM clearing price, which in contrast to the supplier's differentiated buy and sell prices presents zero spread, the energy arbitrage is made possible between the peak (high demand) and the midday (high PV generation) hours. Moreover, the LEM operates in a unified way, with controllability over all the assets and the utilization of the aggregated flexibility to become a competitive advantage that further limits the dependency on the supplier.

4.2.2.2. Retail Buy, Retail Sell, and LEM Prices

In Figure 27 and Figure 28, the hourly profiles of the retail buy price and retail sell price offered by the supplier for both P2G reference and centralised LEM scenarios are presented. For comparability purposes the wholesale prices that are faced by the supplier on its internal operation are also shown. It can be observed that for the centralised LEM case the retail buy price is not defined for the periods where there are no buy transactions with a supplier (Figure 27) price and respectively sell prices are only defined during times the LEM sells to the supplier (Figure 28). Furthermore, Figure 29 illustrates the hourly profiles of the clearing prices of the LEM, which correspond to the dual variables of constraints of 5.29 from D4.4 (balance constraint of the LEM) together with the buy and sell prices offered by the supplier in the P2G reference scenario.

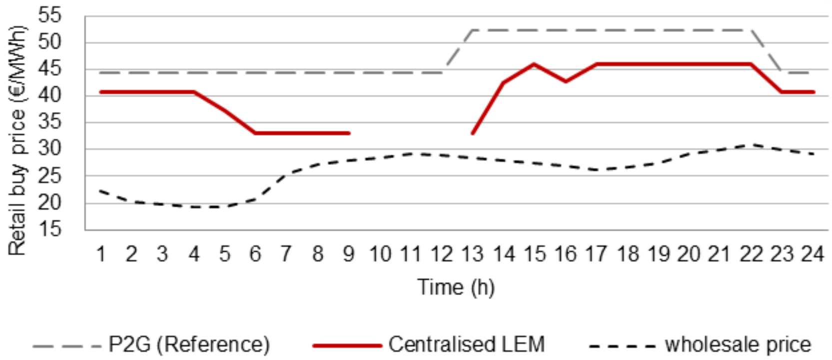


Figure 27: Buy prices offered by the supplier for two scenarios under ToU and flat tariffs.

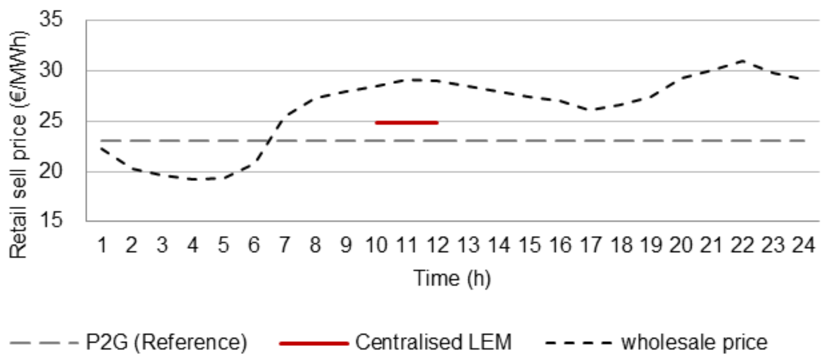


Figure 28: Sell prices offered by the supplier for two scenarios.

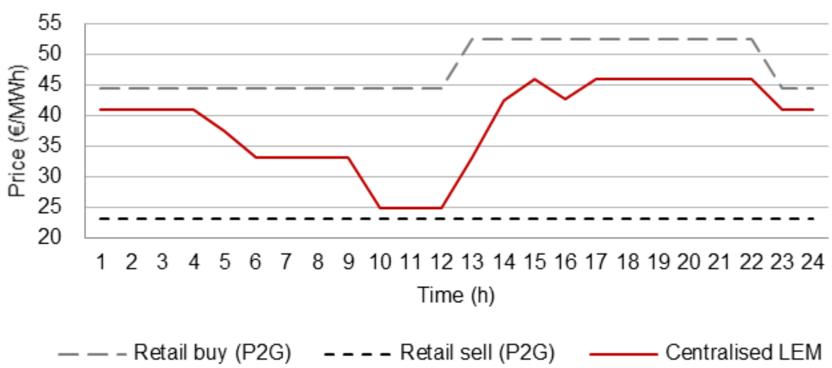


Figure 29: LEM clearing prices for two scenarios under ToU and flat tariffs.

It can be observed from Figure 27 and Figure 28 that the strategic supplier in the P2G reference scenario offers very high buy prices (price level is much higher than the wholesale price) to demanding customers (Figure 27) and very low sell prices (price level is much lower than the wholesale price) to generating customers (Figure 28), trying to exploit the dependency of its served customers. These large differentials between buy and sell prices, constitute excursion of market power, and support the objective of the supplier for maximizing its overall operational profits.

Similarly as the discussion in Section 4.2.1.1, when the LEM is introduced the participants in the market (all the end-users) choose to trade energy locally at the LEM prices, the offered buy prices (Figure 27) and sell prices (Figure 28) are much closer to the wholesale prices in order to attract higher demand and more generation that can compensate the reduction of its served demand and generation caused by the LEM, respectively. Such phenomenon can further demonstrate that the limited effects of LEM on the supplier's strategic potential also exhibit under the ToU price scenario.

4.2.2.3. Supplier's and Customers' Economics

The next step is to quantify and analyse the impact of LEM on the economics of the supplier and its served consumers under the ToU price scenario. Table 4 presents the daily revenue, retail cost, wholesale net cost, and profit of the studied supplier.

Table 4: Economics of Supplier for Two Scenarios under ToU and Flat Tariffs.

Scenario	Revenue (€)	Retail cost (€)	Wholesale net cost (€)	Profit (€)
P2G Reference	378.19	136.61	53.96	189.62
Centralised LEM	181.44	12.041	103.12	66.28

As seen in Table 4, the profit of the supplier in the centralised LEM scenario is significantly (almost three times) lower than that in the P2G reference scenario. This is driven by the significant reduction of supplier's revenue together with the increase of supplier's wholesale net cost, although the retail cost is reduced, which only accounts for a small proportion of the supplier's business cases.

Table 5: Utility of Flexible Consumers for Different Scenarios under ToU and Flat Tariffs.

Scenario	Utility of FC (€)	Profit of MG (€)	Profit of ES (€)	Social Welfare (€)
P2G Reference	123.51	22.99	-	146.50
Centralised LEM	188.34	125.28	4.30	317.92

Moving to the business cases of the customers, Table 5 presents the total (daily) economic surplus of FC, MG, and ES, as well as the customers' total social welfare. It can be presented in Table 5 that the economics of all the customer types (and social welfare) are increased in the centralised LEM scenario with respect to the P2G Reference scenario, since they trade energy based on the LEM clearing prices rather than the high retail buy prices and the low retail sell prices.

4.3 Centralised-based cases

This section discusses some additional centralised case studies. These are optimized centralized P2P market, and both asymmetric and symmetric auction scenarios.

4.3.1. P2P Market Model with Centralized Optimization

The objective of this case study is to simulate the impact of P2P transactions on the LEC. An LEC with 20 prosumers equipped with batteries and PV systems is considered to demonstrate the benefits of P2P transactions. The results will be compared to a scenario without P2P transactions. Is considered that the main grid supports all transactions, and the retailers work as a backup for the energy needs that P2P cannot attend to. A ToU buy tariff with a tri-hourly price and a FiT with a flat price for selling electricity are considered. Figure 30 presents the retailer tariff considered the ToU, the feed-in tariff and the price for the P2P transactions. Retailer tariffs are available online at SU ELETRICIDADE[2] retailer (Portuguese retailer).

As seen in Figure 30, the community has a tri-hourly tariff for buying electricity, and a flat tariff is available for selling. The price of P2P transactions corresponds to the mean between buy and sell price at each moment. This way, the P2P price corresponds to the Mean price presented in Figure 30. Figure 31 illustrates the accumulated load and generation for all 20 prosumers of the energy community.

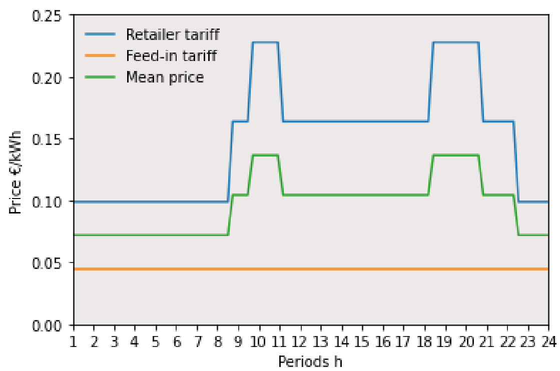


Figure 30: Electricity prices

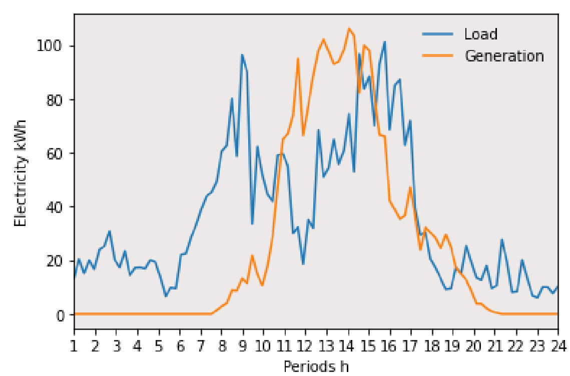


Figure 31: Accumulated load and generation profile

According to the Figure 31 the load of the community presents two different peaks, one at 9:00h (morning period) and other at 16:00h. The community's power generation profile is characterized by peak production at midday, corresponding to a typical profile of a PV generator.

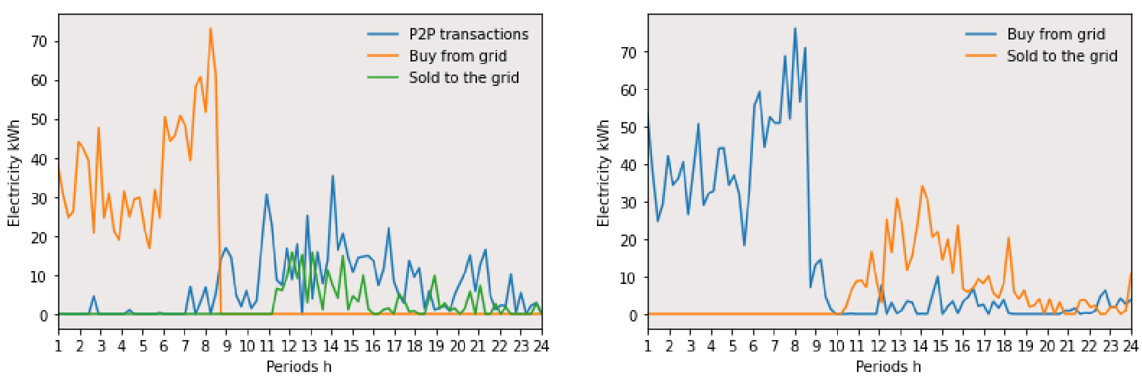
[2] https://sueletricidade.pt/

The results of two different scenarios are presented to prove the viability of the proposed model. Scenario A includes the possibility of carrying out P2P transactions, while Scenario B, in turn, does not allow P2P transactions. Table 6 presents the optimization results for both scenarios.

Table 6: Results comparison

	Total costs (€)	**Costs (€)**	**Revenues (€)**	**Fix Costs (€)**
Scenario A	35.15	47.24	19.81	7.72
Scenario B	41.39	39.62	5.95	7.72

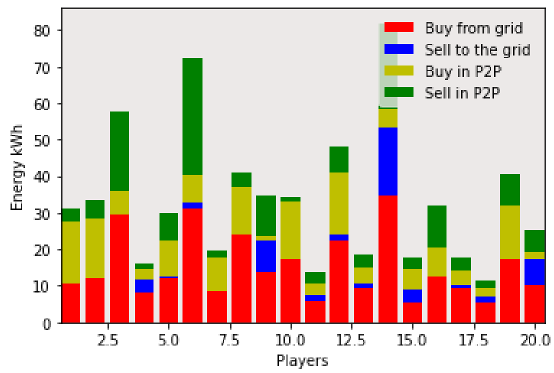
The results presented correspond to one day of operation by community members. Observing Table 6, Scenario A presents a reduction in total community costs of 6.24 € (15%) compared to the total costs of Scenario B. The value of fixed costs is the same for both scenarios as it is an amount paid to the retailer for the supply service. Although in Scenario A the cost of buying electricity is higher than in Scenario B, revenues from the sale of electricity are higher, resulting in a lower total cost value for Scenario A. Figure 32 presents the electricity transaction for the community member considering each period.



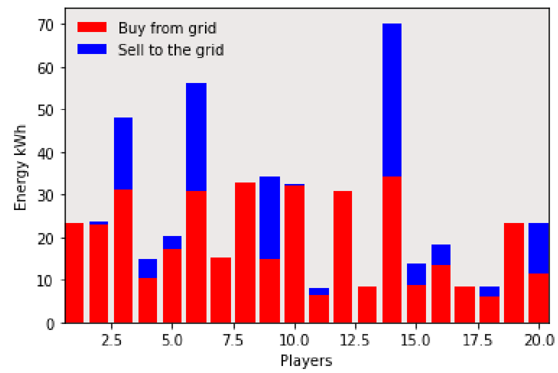
a) *b)*

Figure 32: Electricity transactions considering each period, a) Scenario A and b) Scenario B

Analyzing Figure 32, it is possible to see the electricity transactions considering the different periods of the day. In the early hours of the day, both scenarios have the same behavior, i.e., prosumers purchase electricity at the retailer. Around midday, P2P transactions start to intensify, as PV generation surplus is exchanged among prosumers. Figure 33 presents the accumulated transaction per player for one day of operation.



a)



b)

Figure 33: Accumulated transaction, a) Scenario A and b) Scenario B.

According to Figure 33, prosumer 16 is the member that performs the most transactions in both scenarios. In Scenario A, 163 kWh were traded throughout the day in P2P transactions. Comparing the amount of purchased energy at the retailer: 300 kWh were bought in Scenario A and 382 kWh in Scenario B. Analyzing network sales, Scenario A presents a total of 50 kWh and Scenario B of 132 kWh.

4.3.2. Auction-based Electricity and Flexibility Trading

The following case study aims to demonstrate the use of the double auction (symmetrical pool – see Figure 5a subsection 3.2) trading model for the electricity exchange between the aggregator and several members of the LEC and the use of the single-sided auction (asymmetrical pool – see Figure 5b subsection 3.2) trading model for the aggregator to buy flexibility from its peers whenever the grid's power flow analysis demands. The case study scenario comprises 45 players of a local village and an electricity aggregator aggregating several local communities to participate in the wholesale day-ahead market. The simulation of the aggregator's participation in the wholesale market is out of scope in this deliverable. Furthermore, for simplicity, this scenario only focuses on the local village of these 45 players.

The case study scenario considers data from UiS's Future Energy Lab apartments provided by bY and some consumption datasets from the IEEE PES ISA Open Data Sets repository to represent the different LEC members. Figure 34 illustrates the case study scenario flowchart.

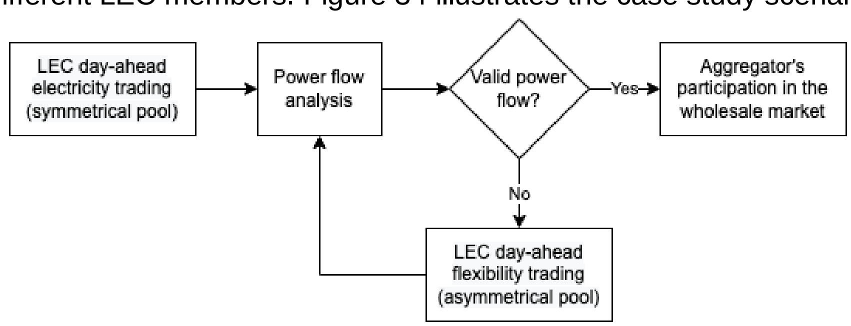


Figure 34. Case study scenario flowchart.

The simulation starts with the execution of the LEC day-ahead electricity market. The goal is for players to buy as much as possible in the local market session to avoid buying energy from the retailer at a higher price. At the end of the session, the aggregator runs a power flow analysis to validate the market outcomes within the local grid, ensuring the grid's security and quality of service. If the power flow analysis of any period returns an invalid result, the aggregator runs an electricity flexibility market for those periods to buy flexibility from its players. The power flow analysis is rerun, being an iterative process until reaching a valid result. After obtaining an acceptable result, the aggregator moves forward to participating in the wholesale market, bidding with the demand/supply from his aggregated players.

The power flow validation must consider the characteristics and constraints of the LEC distribution grid. To this end, the power flow algorithm evaluates the features presented by the following equations. Equations (33) and (34) evaluate the buses' constraints. Equation (33) controls the bus voltage magnitude, which should be between the maximum and minimum limit. The buses' angles are verified by equation (34) and should also respect the minimum and maximum limits.

$$V_{min(i,t)} \leq V_{(i,t)} \leq V_{max(i,t)}, \forall i \in \Omega B, \forall t \in T \tag{33}$$

$$\theta_{min(i,t)} \leq \theta_{(i,t)} \leq \theta_{max(i,t)}, \forall i \in \Omega B, \forall t \in T \tag{34}$$

The maximum allowed power flow in each line is assessed by equation (35).

$$0 \leq FlowS_{(i,j,t)} \leq FlowS_{(i,j)}^{max}, \forall (i,j) \in \Omega_l, \forall t \in T \tag{35}$$

The active and reactive powers, in turn, are constrained by the maximum and minimum capacity that can be transmitted and supplied. Equations (36) and (37) represent these restrictions.

$$P_{SMinLimit(bs)} \leq P_{Supplier(bs,t)} \leq P_{SMaxLimit(bs),} \forall bs \in \Omega_{BS}, \forall t \in T \tag{36}$$

$$Q_{SMinLimit(bs)} \leq Q_{Supplier(bs,t)} \leq Q_{SMaxLimit(bs)}, \forall bs \in \Omega_{BS}, \forall t \in T \tag{37}$$

For this case study, a publicly available distribution grid has been selected. Figure 35 presents a snippet of our village's low voltage power grid.

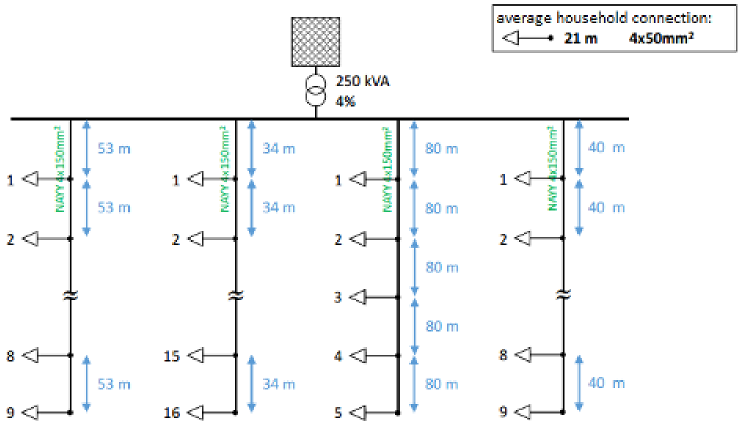


Figure 35. Low voltage distribution grid “village_2” (adapted from [42]).

Each grid’s bus represents a local community player in the simulation. To be interesting for players to participate in the LEM, market prices must always be below the retailers’ prices and above the feed-in tariff. Thus, the aggregator must consider the following price values to keep the LEM interesting to all players:

- the retailers’ prices of each participating player
- the feed-in tariff that prosumers receive when selling energy to the grid
- the wholesale day-ahead price forecast for each period
- the price the aggregator might have to pay to its players for their flexibility in case the power flow evaluation returns an invalid result

Given the above, the players and aggregator bid prices are set above the feed-in tariff and below retailers’ prices. The aggregator must also ensure he has a margin of profit between his bid prices, the costs from participating in the wholesale day-ahead market, and the possible costs of the flexibility market.

4.3.2.1. LEC day-ahead electricity trading

Starting with the LEC day-ahead electricity trading, the symmetrical pool mechanism enables each participating player to submit demand/supply bids for a given period, composed of energy amount and price per unit. To increase the LEC market’s liquidity, the aggregator participates in this market as a seller. The symmetrical pool model calculates the electricity trading for a specific period.

To ease the readers’ follow along, two market periods have been selected based on their outcomes, namely, periods 11 and 21. Figure 36 and Figure 37 present demand and supply curves for periods 11 and 21, respectively.

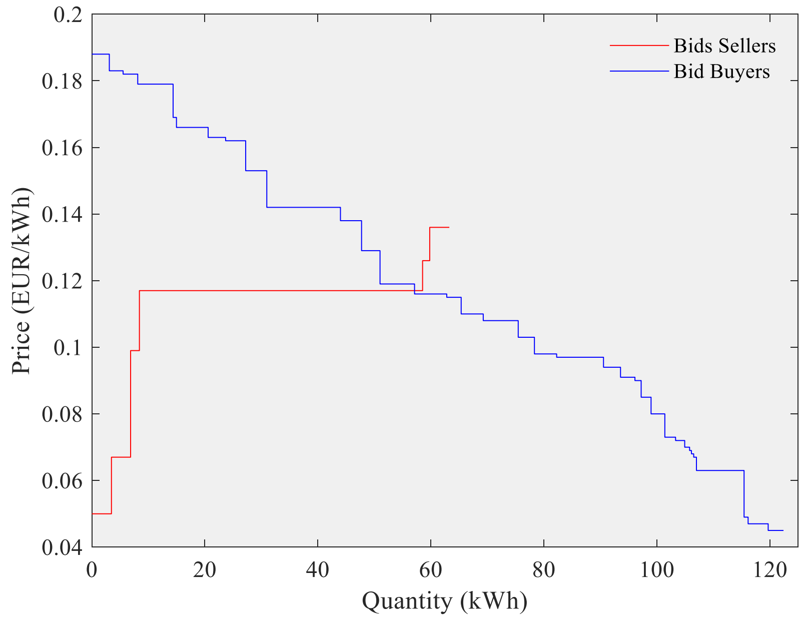


Figure 36. Demand and supply curves of period 11.

Observing Figure 36, it is possible to confirm that, in period 11, the aggregator is not the only player to sell energy as other players (i.e., prosumers) have surplus energy to supply. The point where the curves intersect determines the market price and the amount of energy to trade. It means that, in this period, some players will not be able to trade. In this period, the market price is set at 0.117 EUR/kWh, meaning that buyers offering bid prices higher than the market price and sellers offering bid prices lower than the market price trade in this period pool.

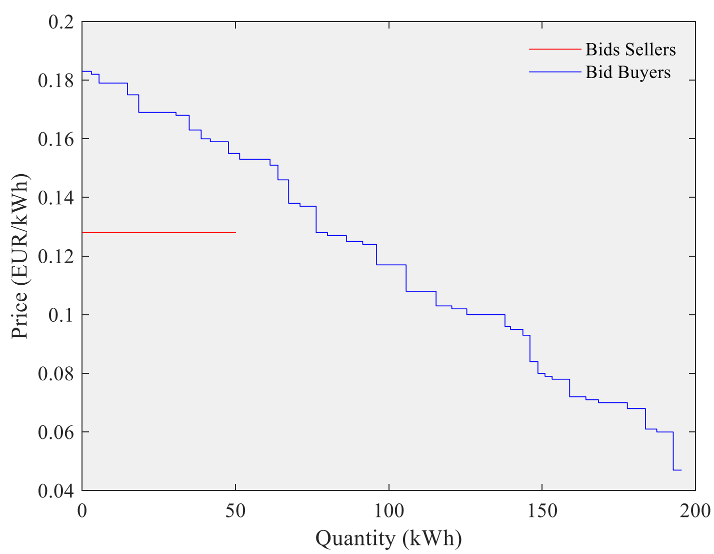


Figure 37. Demand and supply curves of period 21.

On the other hand, in period 21, the aggregator is the only player selling energy in the market pool, as displayed by Figure 37. It is also possible to observe that, in these periods, the supply provided by the aggregator is not enough to satisfy the demand required by the aggregated players, meaning that some of these players will have to buy their energy from retailers. Being the only seller means that the aggregator settles the market price for this period's market pool, i.e., 0.128 EUR/kWh. Once, in this case, the demand and supply curves don't intersect, the aggregator sells all his supply. On the other hand, the players that offered prices above the market price can buy, while the remaining must buy energy from their retailer. Furthermore, players that trade in this period cannot buy all the required energy since the supply is not enough to satisfy the sum of these players' demands. In turn, the total supply is distributed proportionally among these players.

4.3.2.2. Power flow analysis

At the end of the local market session, the aggregator runs a power flow analysis to assess and validate each period's results. According to the power flow evaluation, only period 21 returned an invalid result. Table 7 presents the errors returned by the power flow analysis.

Table 7. Power flow errors for period 21.

Bus	Description
35	Below 0.95p.u by 0.00041911740000000197 p.u.
50	Below 0.95p.u by 6.3249200000004e-05 p.u.
51	Below 0.95p.u by 0.0006467804999999993 p.u.

According to the power flow analysis, the voltage of buses 35, 50, and 51 is below the acceptable minimum value, i.e., 0.95. Thus, an energy reduction of up to 30% must be applied to balance voltage values. To this end, the aggregator runs a flexibility (asymmetric pool) market where he buys energy from its players to reduce their consumption in period 21.

4.3.2.3. LEC day-ahead flexibility trading

Given the invalid power flow in period 21, the LEC aggregator must buy flexibility from its aggregated members. The asymmetrical pool mechanism allows negotiating flexibility, considering a request of a specific amount from the LEC aggregator without specifying a price. The LEC members submit their offers consisting of an energy amount and price per unit for period 21. The asymmetrical pool model calculates the flexibility trading for this event.

Since, in period 21, most players were not able to trade, and the remaining couldn't buy all the required demand, they must purchase energy from their retailers. Therefore, in the flexibility market, they will bid prices above the retailers' tariffs, aiming to reduce their energy bills. Besides, the aggregator defined his bid prices for the symmetrical pool having in mind the possibility of needing to buy flexibility from its players later. Figure 38 shows the amount of energy traded in the asymmetrical pool.

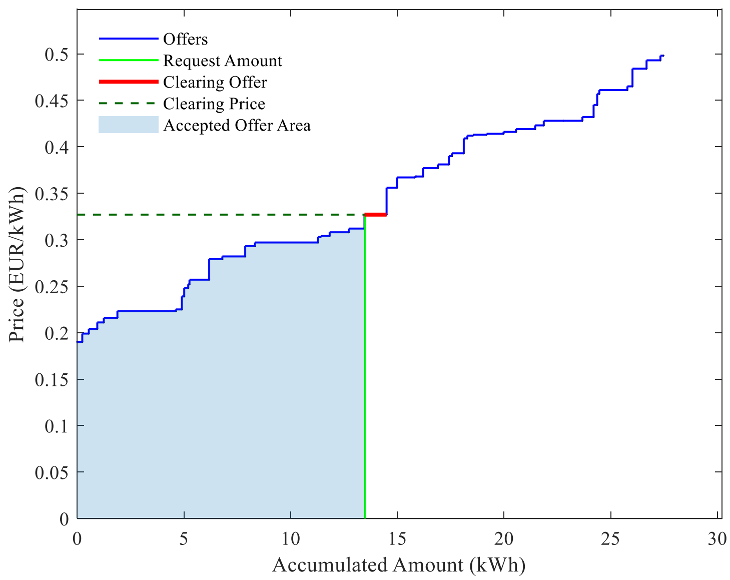


Figure 38. Flexibility pool traded energy.

At the end of the flexibility pool, the aggregator reruns the power flow evaluation, which returns valid this time, concluding the iterative process and defining the final local market day-ahead results. The aggregator's next step is to gather each period's result from the various aggregated communities and participate in the wholesale day-ahead session.

5. Final remarks

This deliverable has described some of the central methodologies behind market design and the case studies that will be simulated in the final iteration of the deliverable. The main market designs presented are based on centralised market models with centralised optimization, and asymmetric/symmetric auctions. The methodology behind these market designs were also discussed thoroughly.

In addition to this, a demo web page for trading in an LEC based on available datasets using blockchain technology to execute transactions was also proposed to illustrate how a blockchain system could serve as an interface from users to the market.

It was shown that implementing a LEM likely results in significant economic improvement for participants in LECs in addition to promoting the development of more renewable energy generation. This scenario should also increase the overall flexibility of the grid due to suppliers not needing to produce as much energy, and consumers likely investing in batteries to store surplus energy.

The simulations that will be run for the final iteration of this deliverable will seek to ascertain how realistic LECs based on the case studies proposed here perform on realistic data and analyse these results relative to the P2G baseline.

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