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Optimal management of cooperative energy communities: impact of agent cooperation

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Abstract. In this work we analyse the profitability of the agents participating in a Local Energy Community (LEC); the agents in these communities can be either passive or active. The main difference is that active agents own generating units that they need to dispatch, whereas passive agents do not own any generating units. The LEC is operated and managed by a coordinating agent that is in charge of all energy exchanges between the agents in the LEC and the external Public Electricity Network (PEN).
We propose a general optimization-based mathematical model to study the interactions among all the participants and to foresee strategies and optimal behaviour within the rules of the LEC. With this model we can compute optimal costs, profits, energy purchases and energy sales, assessing the best configuration for the LEC as a whole and for each individual participant.

Key words. Energy communities, agent cooperation, profit allocation, energy regulation, renewable integration.

Nomenclature

Acronyms

LEC: Local Energy Community
ESS: Energy Storage System
PEN: Public Electricity Network

Indexes

t: Index that represents the daily hours [1..24]
g: Index of agents/users integrated in the community.

Scalars

μ: Coefficient used to compute the price for the energy sold to the PEN, relative to market price λ_t.
C_rate: Charge/discharge maximum ratio of the batteries, relative to capacity $[h^{-1}]$
BL: Battery lifetime [years]
δ: Unit price of energy storage systems [€/kWh]
$\varepsilon_C, \varepsilon_D$: Charge and discharge efficiency of energy storage systems

Parameters

λ_t: PEN market price at time t [€/kWh]
$\mathrm{EG}_{t,g}^{max}$: Maximum Energy Generated at time t by agent g [kWh]
EP_t^{max}: Maximum power that can be supplied by the PEN at time t [kWh]
$\mathrm{ES}_{t,g}^{max}$: Maximum Energy Sold to the PEN at time t by agent g [kWh]
$\mathrm{ED}_{t,g}$: Energy demanded by agent g at time t [kWh]
$\mathrm{GC}_{t,g}$: Generation costs of agent g at time t [€]
$\mathrm{BHC}_{t,g}$: Hourly storage system cost for agent g at time t [€/kWh]
SOC_g^{ini}: Initial stored energy for agent g [kWh]
SOC_g^{max}: Energy capacity of the storage system for agent g [kWh]

Variables

ETBc_t: Total energy charged in the batteries at time t [kWh]
ETBd_t: Total energy discharged by the batteries at time t [kWh]
$\mathrm{SOC}_{t,g}$: Batteries state of charge for each g at time t [kWh]
SOCT^{ini}, SOCT^{min}, SOCT^{max}: Total initial, minimum and maximum state of charge of the batteries [kWh]
$\mathrm{EG}_{t,g}$: Energy Generated by each g at time t [kWh]
$\mathrm{EP}_{t,g}$: Energy Purchased by each g at time t [kWh]
$\mathrm{ES}_{t,g}$: Energy Sold by each g at time t [kWh]
$\mathrm{EBc}_{t,g}$: Energy charged by batteries by each g at time t [kWh]
$\mathrm{EBd}_{t,g}$: Energy discharged by batteries by each g at time t [kWh]
ETG_t: Total Energy Generated in the LEC at time t [kWh]
ETD_t: Total Energy Demanded by the LEC at time t [kWh]
ETP_t: Total Energy Purchased by the LEC at time t [kWh]
ETS_t: Total Energy Sold by the LEC at time t [kWh]
$\mathrm{INC}_{t,g}$: Income from Energy Sold by each g at time t [€]
$\mathrm{EXP}_{t,g}$: Total costs of each g at time t [€]
Z: Profit (Objetive Function) [€]

1. Introduction

The close link between the evolution of human beings and the discoveries related to energy sources and their efficient use is a fact that can be seen throughout our history, from the palaeolithic to the present day [1]. Currently, both in Spain and in most European Union countries, economic and population development is inherently linked to the use of inorganic fuels (mainly fossil and nuclear fuels). Therefore, major economic and environmental problems

arise, scientifically evidenced and quantified since the middle of the 20th century.
Traditionally, new energy sources have been added to the generation mix, not necessarily replacing previous energy sources, at least immediately. However, more recently, technological advances and energy storage systems are increasingly allowing mankind to adopt new stochastic and unreliable energy resources.

2. Legislative framework

The reference milestone for the promotion of the use of renewable energies can be dated back to 1972, at the UN conference in Stockholm, which resulted in the "Declaration on the Human Environment" [2], in view of the alarming signs of environmental deterioration that were occurring on the planet. Since 2016, the European Commission has been committed to involving citizens in the challenge of the energy transition. To boost citizen participation, EU directive 2018/2001 [3] on the promotion of renewable energies was issued; this directive requires member states to guarantee consumers the right to produce, consume, store and sell their own renewable energy. The following year, with EU directive 2019/944 [4], the term *Local Energy Communities* (LECs) was incorporated; this new directive introduced two new legal figures: *Citizen Energy Communities* (CECs) and *Renewable Energy Communities* (RECs).
In Spain, RD 244/2019 [5] and the subsequent decrees for the promotion and boosting of renewable energies have led to the emergence of citizen and/or business groups in many areas, with a common interest in associating to share common energy efficiency projects. The constitution and implementation of LECs, along with their technical-economic management, are predominantly driven by citizen initiative. LECs tend to appear particularly in regions facing energy deficits caused by inadequate infrastructure provided by the local PEN or in areas experiencing high energy prices or a combination of both factors.

3. LEC model

Taking into account that the constitution and physical implementation of a LEC, in a real way, is mainly justified by obtaining an economic profit in the short and medium term, most of the scientific literature related to the optimal operation and management of LECs [7]-[9], is based on mathematical approaches and modelling that aim, either at the maximization of economic profits of the LEC, or at the minimization of the overall operating costs of it, applying different methods and mathematical algorithms [10], [11].

A. Market and local energy community modelling

The local community proposed for this study, is flexible in terms of the number of prosumer (active) and/or consumer (passive) users, as well as in the storage system for energy surpluses. Other authors, such as [12]-[14], have designed different LEC configurations to also optimize their operation.
Our objective in this first stage of the study is to find out whether it is economically profitable to set up a small LEC, made up of agents that are neither large generators nor large consumers, resembling a community of close neighbours. However, the mathematical model developed and its software implementation are both suitable for any size of LEC.
The problem has been conceptually approached as an energy community equivalent to a "black box" seen from the outside, in which we have a series of inputs and outputs according to the following scheme:

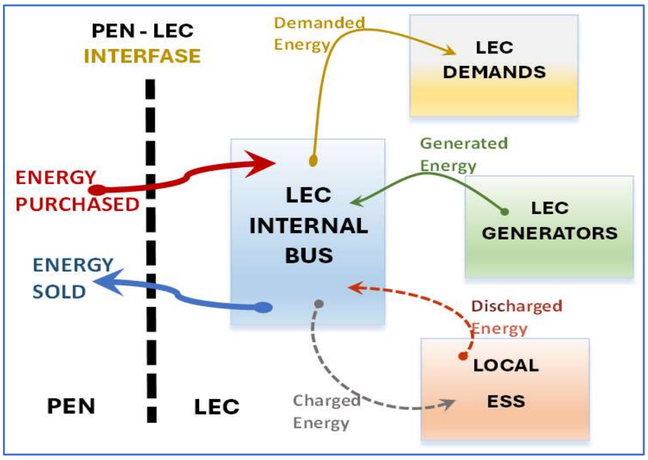

Figure 1. Simplified LEC energy exchange scheme.

Observe that in figure 1, the LEC internal bus is used to connect demands, generation and storage from the individual agents among themselves and to the external network.

B. Key features of the proposed model

The LEC optimization algorithm seeks to maximize the profit of all the agents, who need to satisfy their own total demands. Our simulated energy system has been designed with the following characteristics:

1. Energy association: the LEC is formed by n agents, of which k are active prosumers that can generate and demand energy and the other n-k are passive (they only demand energy).
2. Agents may have storage systems, or even participate in a community battery bank.
3. The system never runs out of energy; it is interconnected to the general grid, which is always capable of supplying the energy needed in case the energy generated internally is not enough or its cost is higher than that offered by the grid.
4. The generating cost of the agents has been estimated according to the generation technology of each one of them.

We want to determine the mode of operation that is most profitable to the agents in the LEC, so that they can choose the most convenient form of association to the LEC. In order to analyse the main options present in worldwide regulations and in the real operation of small-scale energy generators, we have identified three main features that must be considered. The first one is *coordination*: participants in the LEC may coordinate among themselves to optimally exchange energy inside the LEC and between the LEC and the PEN. The second feature considered is *storage*: participants in the LEC may own Energy Storage Systems that need to be considered in the optimal operation of the LEC. Finally, the third feature studied is *network payments*: we consider the option that the external PEN will have to pay the agents in the LEC for the energy that the LEC injects into the PEN. Considering each of these three possible alternatives, we can obtain 8 possible configurations of the system considered.

C. Mathematical models

To implement the 8 possible configurations mentioned above, two different mathematical models are needed, the first one is for uncoordinated operation and the second one for coordinated operation of the agents within the LEC:

1) Mathematical model for uncoordinated cases

Objective function for uncoordinated cases (one objective function for each individual agent):

$$max\ Z_g = \sum_{t=1}^{24} \left(INC_{t,g} - EXP_{t,g}\right) \quad (1)$$

Constraints:

$$INC_{t,g} = \mu \cdot \lambda_t \cdot ES_{t,g}\ , \forall t \quad (2)$$

$$EXP_{t,g} = EP_{t,g} \cdot \lambda_t + EG_{t,g} \cdot GC_{t,g} + BHC_{t,g}\ , \forall t \quad (3)$$

$$BHC_{t,g} = \frac{SOC_g^{max}}{365 \cdot BL}\ , \forall t \quad (4)$$

$$EP_{t,g} + EG_{t,g} + EBd_{t,g} = ES_{t,g} + EBc_{t,g} + ED_{t,g}, \forall t \quad (5)$$

$$EP_{t,g} \leq EP_t^{max}\ , \forall t \quad (6)$$

$$ES_{t,g} \leq ES_t^{max}\ , \forall t \quad (7)$$

$$EG_{t,g} \leq EG_t^{max}\ , \forall t \quad (8)$$

$$EBc_{t,g} \leq EBS_g^{max} \cdot C\_rate \cdot \varepsilon_C\ , \forall t \quad (9)$$

$$EBd_{t,g} \leq EBS_g^{max} \cdot C\_rate \cdot \varepsilon_D\ \forall t, \quad (10)$$

$$SOC_{t,g} = SOC_{t-1,g} + EBc_{t,g} - EBd_{t,g}\ , \forall t > 1 \quad (11)$$

$$SOC_{t1,g} = SOC_g^{ini} + EBc_{t1,g} - EBd_{t1,g} \quad (12)$$

$$SOC_g^{ini} = 0.5 \cdot SOC_g^{max} \quad (13)$$

Equation (2) computes the income, equations (3)-(4) compute the total costs, (5) states the energy balance, (6)-(8) impose limits to variables, (9)-(10) limit ESS operation and (11)-(13) model ESS operation.

2) Mathematical model for coordinated cases

In the coordinated case all units must be dispatched and operated at the same time in order to profit from the coordination of the agents, hence, only one large optimization problem is needed. Again, in this problem revenues are obtained from the sale of energy surpluses and expenses are derived from the generation costs of the energy community, costs of batteries for energy storage and costs of purchasing energy from the grid.

Objective function for coordinated cases:

$$Max\ Z = \sum_{t=1}^{24} \sum_{g=1}^{k} (INC_{t,g} - EXP_{t,g}) \quad (14)$$

The coordinated model includes the previously defined constraints (2)-(13) for each agent. Also, some additional constraints are needed in order to include the coordinated nature of the model.

Additional constraints:

$$ETP_t + ETG_t + ETBd_t = ETSG_t + ETBc_t + ETD_t, \forall t \quad (15)$$

$$ETG_t = \sum_g^k EG_{t,g} \qquad \forall t \quad (16)$$

$$ETD_t = \sum_g^k ED_{t,g} \qquad \forall t \quad (17)$$

$$ETP_t = \sum_g^k EP_{t,g} \qquad \forall t \quad (18)$$

$$ETBc_t = \sum_g^k EBc_{t,g} \qquad \forall t \quad (19)$$

$$ETBd_t = \sum_g^k EBd_{t,g} \qquad \forall t \quad (20)$$

$$SOCT^{max} = \sum_g^k SOC_g^{max} \quad (21)$$

$$SOCT_t = SOCT_{t-1} + ETBc_t - ETBd_t,\ \forall t > 1 \quad (22)$$

$$SOCT_{t1} = SOCT^{ini} \cdot SOCT^{max} + ETBc_{t1} - ETBd_{t1} \quad (23)$$

$$SOCT^{ini} = \sum_g^k SOC_g^{ini} \quad (24)$$

Constraint (15) forces the whole community to be balanced and interact as a single prosumer, seen from the general grid. In this equation the new variables are the summation of each agents' variables, as defined in (16)-(21). Equations (22)-(24) model the constraints related to ESS operation.

4. Case study

Having defined the basic characteristics of the energy community in section 3B, the next step is to discern the mode of operation that most profits its users or agents, so that they can choose the most convenient aggregation modality for them.

However, even though our general model considers all the operating cases of our LEC, for this work we will not consider the option of the LEC participants owning batteries or other energy storage systems (due to the high cost of these systems and their short lifetime in relation to the generation systems). The main reason is that in this early phase of our study, our objective is to show the effects of coordination between users within the LEC, whether they are active or passive. Therefore, the following modes of operation within the LEC will be analysed and compared:

Case 1-Uncoordinated: Agents act independently (it would not really be a LEC): passive agents buy their energy directly from the PEN at the market price and active prosumers can sell any amount of energy to the PEN with a reduction factor on the market price μ= 0,9.

Case 2-Coordinated: The users coordinate among themselves, so that the passive agents buy first the surplus energy from the active prosumers within the LEC (if the generation price is lower than the market price in that time slot). The purchase of internal energy in the LEC is weighted with a reducing factor on the market price μ= 0,9 (as an incentive for passive prosumers). On the other hand, both active and passive prosumers distribute the coordination profits proportionally to both what they sell and what they buy.

A. *Data Input*

All the simulations have been carried out for a period of one day divided into 24 1-hour time periods. The modelled user community is based on an initial configuration of 8 participants in which each one can behave as an energy generator, as a demander-consumer or as both.

Table I. Input data used for LEC simulation

	Daily Agent Total Demand (kWh)	*Generation technology*	*Generation Cost (€/kWh)*	*Hourly Maximum Generation (kWh)*	*Total Daily Generation Capacity (kWh)*
Ag1	5020	PV	0,113	710,5	5679,5
Ag2	7530	Wind	0,082	728,0	3518,0
Ag3	3347	Biomass	0,185	150,0	3600,0
Ag4	2510	Diesel	0,205	100,0	2400,0
Ag5	1004	none	-	-	-
Ag6	1506	none	-	-	-
Ag7	669	none	-	-	-
Ag8	2510	none	-	-	-

Agents Ag1 through Ag4 are the active prosumers, as they have the capacity to generate energy, as well as being demanders. In contrast, agents Ag5 through Ag8 are passive agents, i.e. they are only energy consumers.
Note that the characteristics of the proposed LEC are compatible with a LEC with greater demand than its generation, as can be verified by observing the columns of Table 1.
The following figure shows the distributions of power generation capacities according to agents' technology:

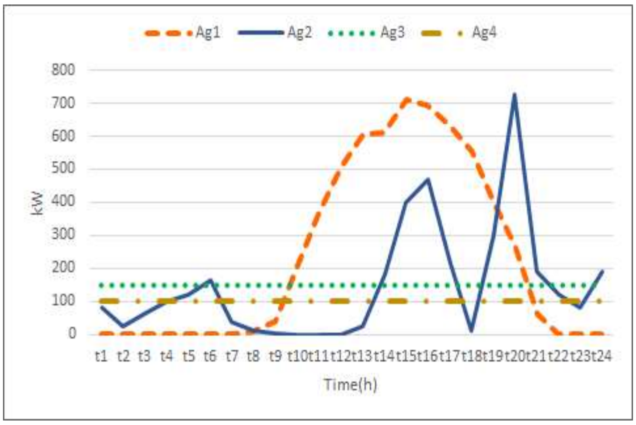

Figure 2. Active prosumers' Power Generation capacities

As can be seen in Figure 2, agents Ag1 and Ag2 have solar and wind technologies respectively, and therefore behave stochastically over the 24-hour period. In these represented data, note that there are time slots in which these technologies would not generate any energy, as is the case of the period t1-t8 for agent 1 and the period t10-t12 for agent 2. On the other hand, the generation of the agents Ag3 and Ag4 (biomass and diesel respectively) is constant over time and therefore they are not stochastic energy producers and can be dispatched by the agents as needed.

The price at which energy can be purchased on the market, depending on the period, has been considered variable and its value for the simulation is shown in the following figure, compared with the marginal costs of all the generators in the LEC:

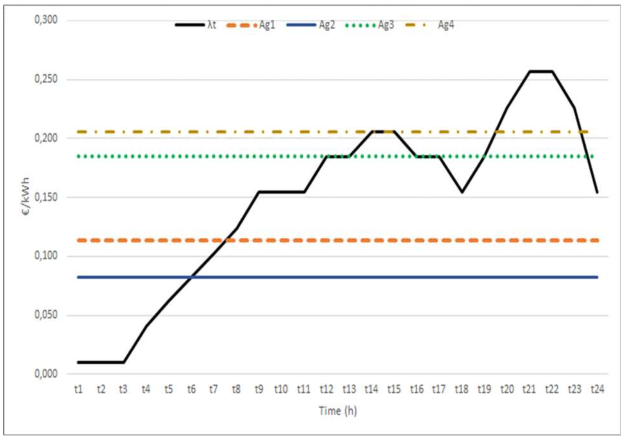

Figure 3. Energy costs: market prices vs. prosumer prices

Also note that, for time period 2 all generators have costs higher that the network price and hence it would be advantageous for all of them to buy from the PEN; and, conversely, the network price at time period 21 is higher than the generating costs for all the generators, and hence buying from the network will be very expensive at this time, and will only be done if all the generators are already at capacity.
On the other hand, the price at which the electricity market purchases surplus generation from prosumers has been set at 90% of the market purchase price i.e. μ= 0,9. Thus, the economic exchange resulting from the energy flow at the LEC-PEN interface is always to the advantage of the PEN.

B. *Simulation results*

After entering the data from Table 1 into the model, the following results have been obtained, with the parameters specified for Case 1 and Case 2:

Table II. Energy results after simulation of cases 1 and 2

CASE	ETD (kWh)	ETG (kWh)	ETP (kWh)	ETS (kWh)
1	24216	9912,8	18359,3	4056,1
2	24216	9691,5	15134,4	609,9

Table III. Economic results after simulation of cases 1 and 2

CASE	Total Generation Costs (€)	Total Purchase Costs (€)	Total Agents Costs (€)	Total Income (€)	Net Profit (€)
1	1130,4	3045,6	4176,0	690,7	-3485,3
2	1087,3	2447,3	3534,6	110,5	-3424,1

Note that in both cases the value of net profits are negative, this must be understood as LEC economic losses; however, it must be taken into account that these economic losses include the *utility* that the use of this energy means for the users of the system and should not be considered merely as an unprofitable business. Note that for LECs with higher penetration of cheap generation and a smaller ratio of internal demand, the profit numbers could actually be positive.

By comparing the last column (Net Profit) in both cases, we can see that there is a clear difference in economic losses, with 61.2€ in favour of Case 2 compared to Case 1. This improvement in profit is exclusively due to the fact that agents can coordinated among them within the LEC (exchanging energy flows generated and demanded internally).
Figures 4 and 5 show the amount of energy exchanged by all agent over a full 24-hour period, for each case.

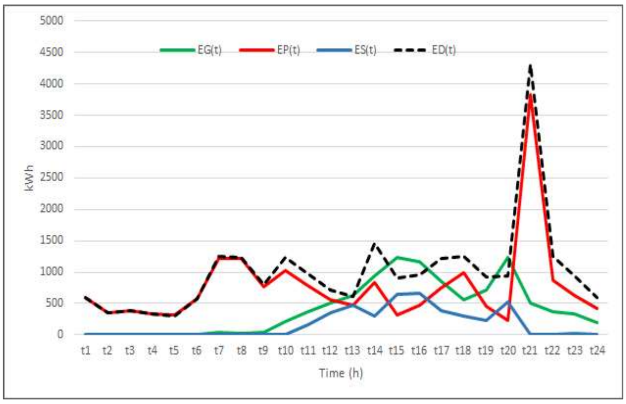

Figure 4. Case1: Graphical results for exchanged energies.

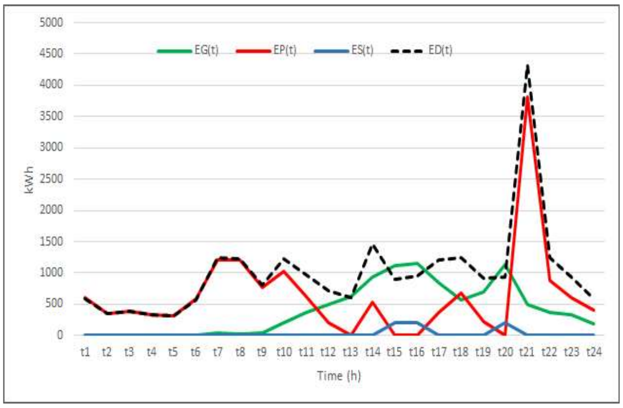

Figure 5. Case2: Graphical results for exchanged energies.

From the observation of figures 4 and 5, we can deduce that, despite the lower total revenue from energy sales to the grid in Case 2, the profit has improved (decreased economic losses). This can be clearly seen in the figures if we compare both in the period t13-t18, in which (although the energy generated remains very similar in both cases), in Case 2 hardly any energy has been acquired from the PEN and at the same time, no energy has been sold to the PEN. This has occurred because the energy generated in Case 2, instead of being sold to the PEN, has been transferred within the LEC to cover internal demands.
This internal sale-purchase of energy is initially more beneficial for the consuming agents (since they acquire it at a price μ= 0,9 cheaper than the market price) but also the generating agents receive their proportional part of this benefit-savings for buying less from the PEN and also for the energy that they do sell to the PEN (when the LEC does not need it and it is profitable to sell to the PEN).

It can be verified that at any instant t of the 24-hour simulation, the energy balance is also fulfilled. For this purpose, instant t=11h has been taken as an example, since, as we can see in figures 4 and 5, both cases behave differently at that time. Thus, the results obtained for both cases at instant t=11h are summarised in tables 4 and 5 below:

Table IV. Energy results after simulation: case 1 and 2 at t=11h

CASE	ED (kWh)	EG (kWh)	EP (kWh)	ES (kWh)
1	984,2	365,5	780,2	161,5
2	984,2	365,5	618,7	0,0

Table V. Economic results after simulation: case 1 and 2 at t=11h

CASE	Generation Costs (€)	Purchase Costs (€)	Total Agents Costs (€)	Incom (€)	Net Profit (€)
1	153,4	23,9	177,3	1,5	-175,8
2	41,4	92,8	134,2	0,0	-134,2

From the results of tables 4 and 5 we can conclude that in the same way as occurred in the complete 24-hour simulation, at hour t=11h a better economic result is produced due to coordination (Case 2), even in a situation in which the LEC does not sell energy to the PEN.

Individual results of each agent after profit allocation from the sale to PEN.

Table VI. Comparison results

	Case 1 vs Case 2 Comparison			
	Profit Case 1	Profit Case 2	Profit Incr. % by Coord.	Profit Incr. by Coord (€)
Ag1	-533,4	-506,5	5,04%	-26,9
Ag2	-973,2	-962,1	1,14%	-11,1
Ag3	-548,4	-543,9	0,82%	-4,5
Ag4	-424,5	-419,9	1,08%	-4,6
Ag5	-174,5	-172,0	1,43%	-2,5
Ag6	-261,7	-258,0	1,41%	-3,7
Ag7	-133,5	-131,6	1,42%	-1,9
Ag8	-436,1	-430,1	1,38%	-6
Total	-3.485,3	-3.424,1	1,76%	-61,20

In the first 2 columns of table 6 (above), we can see the profits obtained by each agent individually.
The allocation method used for the distribution of profits generated in the LEC thanks to internal coordination is described next in a two-step process. In the first step, for each hour and knowing the optimal resulting generation and consumption schedule, the amount saved is computed as net payments to the network if coordination was not allowed minus net payments to the network when coordination is allowed. Note that net payments include both payments to the PEN when energy is bought from it and money received from the PEN when energy is injected into it. In the second step, the total hourly savings is divided by two, one half of the amount is allocated to all the generators in amounts proportional to the energy generated during the hour and the other half is divided among all the consumers in amounts proportional to the energy consumption in the hour.
Therefore, as we can see in the last column of table 5, coordination allows a total profit of 61,20 € (which in this case, being a negative number, must be interpreted as a decrease in economic losses). This amount of money saved is exclusively due to the fact that the LEC agents coordinate with each other.
Coordination allows the agents to buy energy within the LEC cheaper than the price offered by PEN (this is part of

the benefit) and also allows the generating agents to sell internally in the LEC more expensively than what PEN would pay for their generated energy (this is the other part of the benefit or saving obtained between Case 1 and Case 2).
Other types of distribution of benefits and costs have been proposed in research prior to this study [14]-[16].

5. Conclusion

According to the results obtained after the simulations carried out with our simplified LEC model, we can conclude that significant benefits are obtained when agents coordinate with each other, exchanging between them both the energy generated by the active agents such as purchasing the energy demanded preferably within the LEC (Table 5). This occurs even with the proposed LEC model, that is mostly energy demanding, with a limited amount of generation. In our model, this economic profit is distributed between the generators and the consumers in a fair manner, which is more profitable to the agents than the exchange with the PEN.
For energy exchanges and economic management between the LEC and the PEN to be carried out fairly, it is necessary to implement a coordinating agent (which we have called LEC Internal Bus in figure 1); this coordinating agent collects and manages both the energy demand of the LEC and the energy that is generated in it. In addition, this LEC coordinating agent oversees the distribution of the possible benefits.
Our model and simulations are based on linear mathematical programming problems which can be solved easily with readily available software and computers.
Our proposed model formulation also features Energy Storage Systems, although we have not included them in the presented case studies, this is left as future work extending the present results to a more general implementation of LECs. In addition, for future work, we intend to analyse the influence of the μ value and therefore, the possibility that this could be a technology-dependent parameter, trying to provide incentives to specific technologies.

Acknowledgement

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