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UNIVERSIDAD PONTIFICIA

ICAI

Grado en Ingeniería en Tecnologías Industriales

Trabajo de Fin de Grado

APPLICATION OF OPTIMIZATION PROCEDURES TO THE PLANNING AND OPERATION OF LOCAL ENERGY COMMUNITIES

Autor: Juan Bosco García de Madariaga Orejas

Director: Alberto Borghetti

Madrid

2021

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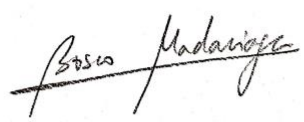

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Autor: Juan Bosco García de Madariaga Orejas

Director: Alberto Borghetti

Madrid

2021

Agradecimientos

A mi director, Alberto Borghetti,

por su ayuda en el proyecto.

MEMORIA DESCRIPTIVA

Introducción

En este Proyecto se realiza un estudio de una Comunidad Local de Energía (siglas LEC en inglés) especifica, de tal manera que se pueda verificar su rentabilidad en comparación con otras comunidades sin transacciones internas. Para ello, se minimizan los costes totales de intercambio de energía de la comunidad con la red pública mediante un procedimiento de optimización para un día (24 horas).

La diferencia clave entre una Comunidad Local de Energía con otras comunidades se basa en la posibilidad de intercambio de energía entre usuarios.

La intencionalidad de este proyecto es la de incentivar el incremento en la introducción de Comunidades Locales de Energía con el fin de reducir tanto los costes como las pérdidas de energía. De esta manera, el proyecto pretende ser rentable y, en general, sostenible.

Estado de la cuestión

Este proyecto plantea un análisis sobre una comunidad en concreto, de tal manera que se puedan demostrar sus beneficios. En este proyecto en concreto, se analizan los cambios al incrementar el número placas fotovoltaicas de los usuarios. Además, el uso de baterías de almacenamiento de energías es clave en la reducción de pérdidas de la comunidad, pero su rentabilidad entre costes de instalación y mantenimiento con respecto al ahorro diario de coste energético debe ser analizado en cada situación.

En otros proyectos, recientemente se ha podido demostrar la rentabilidad de la implantación de las Comunidades Locales de Energía en ciertas comunidades concretas.

El conflicto para futuros proyectos queda en analizar si es rentable la instalación de paneles fotovoltaicos para aumentar aún más la rentabilidad de dichas comunidades, así como la instalación de baterías de almacenamiento de energía, según cada situación. A nivel medioambiental, los beneficios son evidentes. Cabe destacar que para que la instalación de paneles fotovoltaicos sea rentable ha de realizarse en una zona donde la incidencia solar sea óptima. Además, se deben analizar los conflictos de interés entre los usuarios para cada situación.

En este proyecto se realiza una aproximación de corriente continua a los flujos de potencia, lo cual es útil para obtener una estimación de los beneficios económicos de manera rápida y sencilla, pero no es exacta y se debería de computar un modelo más refinado si se quieren representar de manera efectiva las pérdidas de potencia

En resumen, un análisis de cada comunidad debe ser desarrollado previamente para optimizar las pérdidas sin conflictos de interés.

Motivación

Si bien es cierto que hay determinados proyectos que verifican la rentabilidad de las Comunidades Locales de Energía, siempre es beneficioso realizar un estudio concreto en otra comunidad, dado que cada comunidad dará unos resultados diferentes. Cada comunidad se puede interpretar con transacciones internas diferentes y con unos datos de consumo y generación distintas. Además, se pueden plantear programas de optimización de diferentes formas, estableciendo horizontes de tiempo o funciones objetivas más o menos complejas.

La incentivación hacia la introducción de las Comunidades Locales de Energía es importante no solo a nivel económico sino también a nivel ambiental. Dichas comunidades se ven favorecidas por la introducción de paneles fotovoltaicos, los cuales no generan residuos al tratarse de energía renovable. En concreto, dichas comunidades favorecen los objetivos marcados por la Comisión Europea hacia un futuro sostenible sin emisiones de CO_2.

Objetivos del proyecto

Los objetivos del proyecto son los de demostrar la rentabilidad de la introducción de transacciones internas en una comunidad concreta, así como la rentabilidad del aumento de paneles fotovoltaicos en dicha comunidad. Esta rentabilidad se plantea con el foco en los costes de intercambio de la comunidad con la red pública. Cabe destacar que ciertos usuarios pueden verse perjudicados por la introducción de dichas comunidades a pesar de que los costes globales y pérdidas de la comunidad en general se vean reducidos. Por ello, un análisis de cada comunidad en concreto es necesario.

Con este modelo de programación en corriente continua se pretende evaluar de manera rápida y aproximada la rentabilidad de las anteriormente mencionadas Comunidades Locales de Energía. Dicho modelo puede ser extrapolado a otras comunidades con diferentes datos de consumo y generación, o diferentes relaciones en cuanto a transacciones internas entre los usuarios.

Metodología del trabajo

Para realizar dicho proyecto se ha acudido a la plataforma de programación AIMMS. Las restricciones incluidas en el modelo serán las necesarias para forzar que el modelo sea lineal, en concreto de enteros mixtos, de tal manera se pueda resolver por medio de CPLEX 20.1.0, la versión más reciente de 2021 del paquete de optimización lanzado al mercado por IBM.

Para que el modelo sea lineal, se asume un modelo aproximado de corriente continua, lo cual permite una primera estimación para analizar los flujos de potencia. Para una mejor estimación de las pérdidas de potencia se debería realizar un modelo más complejo. Las restricciones utilizadas en el modelo son las justas y necesarias para reproducir de manera correcta los flujos de potencia entre comunidades y con la red pública.

En nuestro modelo concreto, se asume una comunidad de trece usuarios, donde cada usuario dispone de generación fotovoltaica, consumo y almacenamiento de energía en batería. Cada usuario se asume con unos datos numéricos diferentes según su situación. Un análisis más profundo de nuestra comunidad concreta se puede observar tanto en el trabajo completo como en el abstracto inicial.

Recursos a emplear

Para realizar dicho proyecto se ha acudido a la plataforma de programación AIMMS. Las restricciones incluidas en el modelo serán las necesarias para forzar que el modelo sea lineal y de tal manera se pueda resolver por medio de CPLEX 20.1.0, la versión más reciente de 2021 del paquete de optimización lanzado al mercado por IBM.

APLICACIÓN DE PROCEDIMIENTOS DE OPTIMIZACIÓN A LA PLANIFICACIÓN Y OPERACIÓN DE COMUNIDADES ENERGÉTICAS LOCALES

Autor: García de Madariaga Orejas, Juan Bosco.
Director: Borghetti, Alberto.
Entidad Colaboradora: Università degli Studi di Bologna

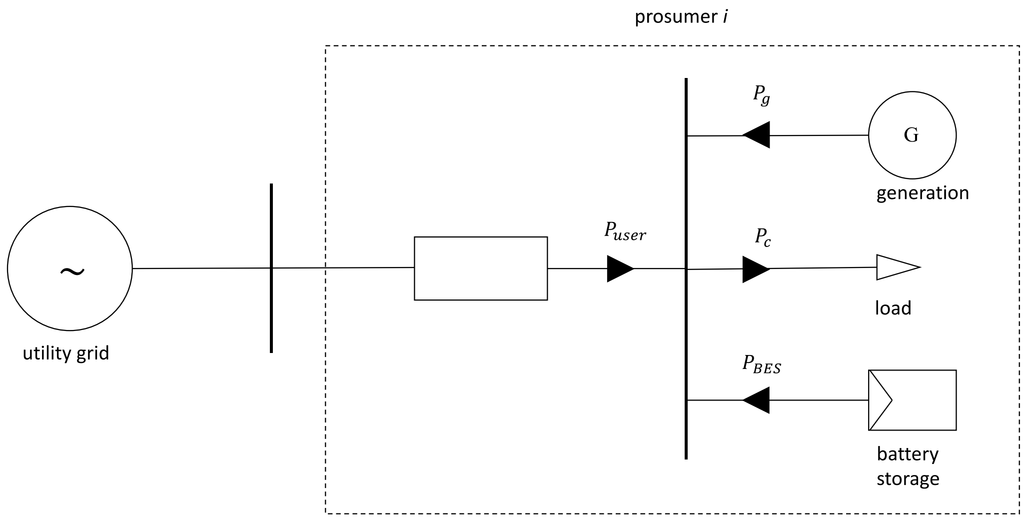
RESUMEN DEL PROYECTO

1. Introducción

En este Proyecto se realiza un estudio de una Comunidad Local de Energía (LEC) especifica, de tal manera que se pueda verificar su rentabilidad en comparación con otras comunidades sin transacciones internas. Para ello, se minimizan los costes totales de intercambio de energía de la comunidad con la red pública mediante un procedimiento de optimización para un día (24 horas).

2. Restricciones del Modelo

En nuestra comunidad específica, se asume que cada prosumidor (consumidor y productor de energía al mismo tiempo) tiene una generación fotovoltaica, un consumo y una batería de almacenamiento de energía. Las pérdidas son despreciadas.



Cada prosumidor está restringido por la siguiente ecuación

$$P_{user} = P_c - P_g - P_{BES}$$

y las direcciones positivas de dichos parámetros o variables se pueden observar en la figura anterior. La potencia reactiva se asume nula, aproximando a un modelo de corriente continua.

La potencia de almacenamiento P_{BES} de cada prosumidor queda definida por la siguiente ecuación

$$P_{BES} = P_{BES}^{+} - P_{BES}^{-}$$

donde P_{BES}^{+} y P_{BES}^{-} son variables positivas limitadas por la máxima potencia de cada batería. Las pérdidas de carga y descarga de la batería son despreciadas.

El nivel de energía de cada batería se define en la siguiente ecuación

$$E_t = E_{t-1} - (P_{BES,t} + \ell_{charge,t} + \ell_{discharge,t}) \cdot \Delta t$$

la cual está limitada a estar entre 10-100% de la capacidad de la batería. El nivel de energía al principio y al final del horizonte de tiempo T está limitado a ser igual al valor inicial de la capacidad de la batería.

Definimos las variables P_{grid}, P_{buy_grid} y P_{sell_grid} para minimizar los costes de intercambio de energía con la red pública, limitadas por las siguientes restricciones:

$$P_{grid} = P_{buy\_grid} - P_{sell\_grid}$$

$$P_{user} = P^{+} - P^{-}$$

$$|P_{user}| = P^{+} + P^{-}$$

$$P_{buy\_grid} \leq P^{+}, \qquad P_{sell\_grid} \leq P^{-}$$

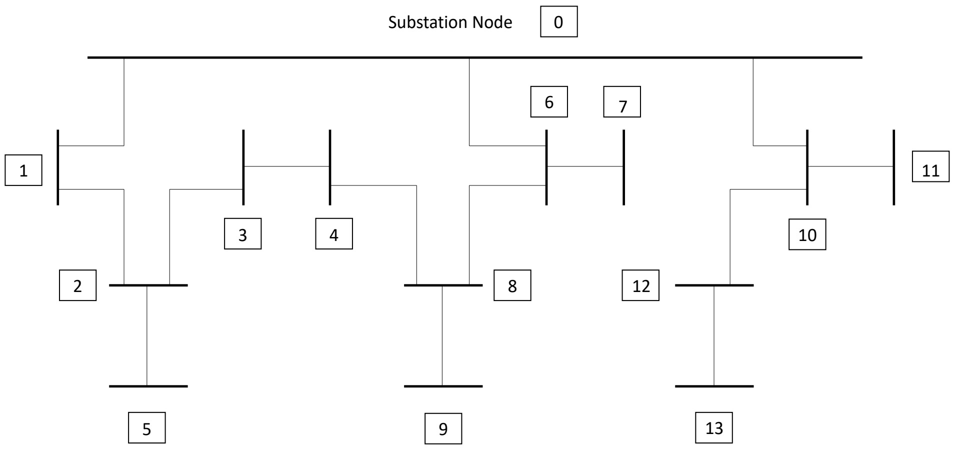
El flujo de energía de corriente continua queda limitado por la siguiente restricción

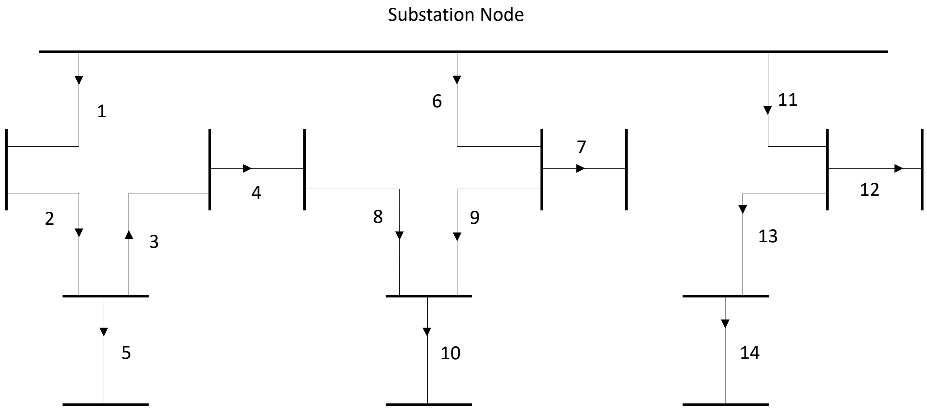
$$P_{km} = \frac{\theta_{km}}{x_{km}}$$

donde θ_{km} representa la diferencia de ángulos entre los nodos k y m, y x_{km} representa la reactancia de la línea entre dichos nodos. El modelo está limitado también por las ecuaciones de equilibrio de entrada y salida de potencia.

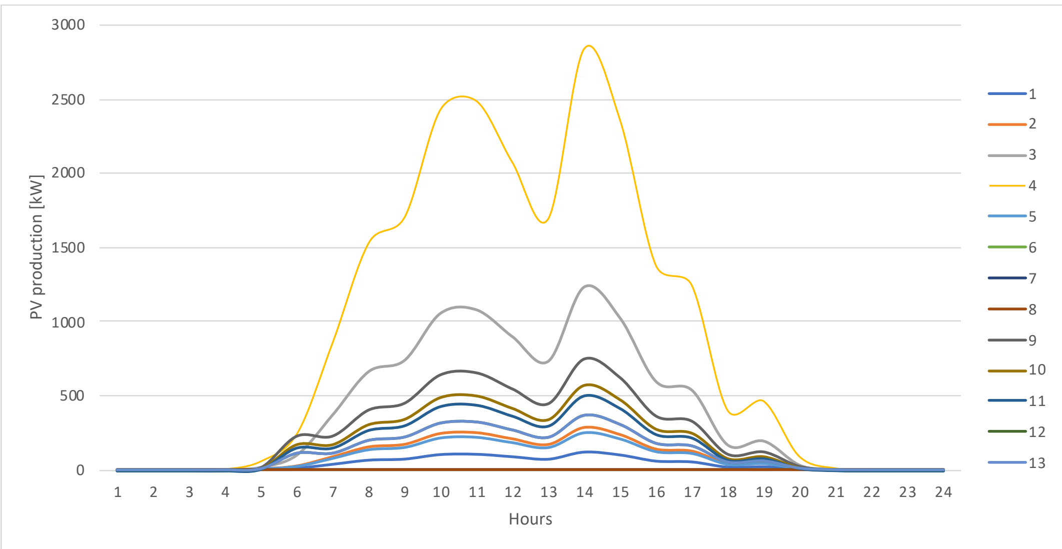
3. Descripción y Datos del Modelo

Asumimos una comunidad con 14 nodos, donde uno de ellos representa la red pública, mientras que los trece restantes representan a los prosumidores. El modelo queda definido en las siguientes figuras.

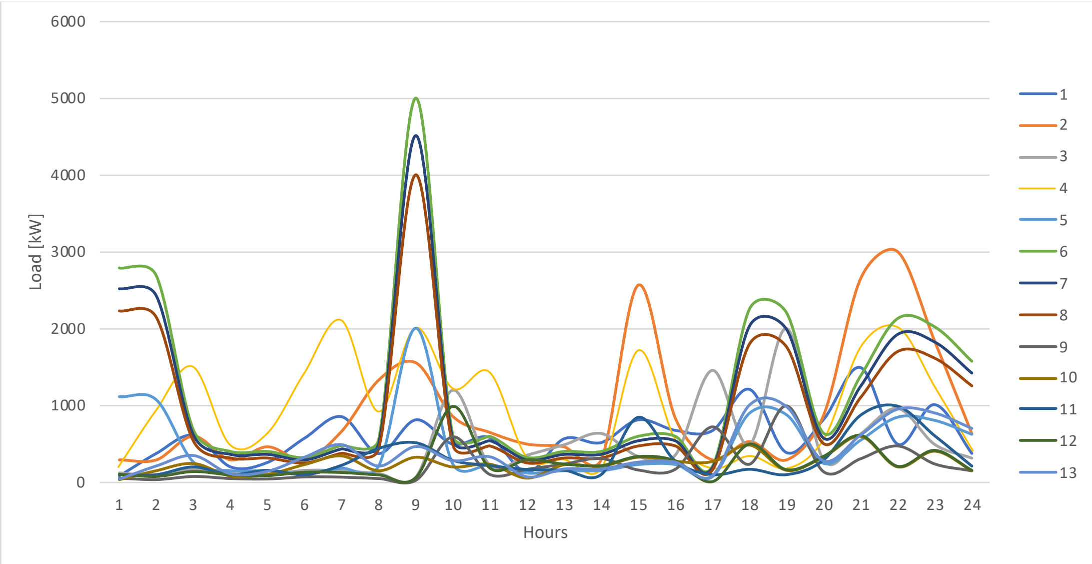


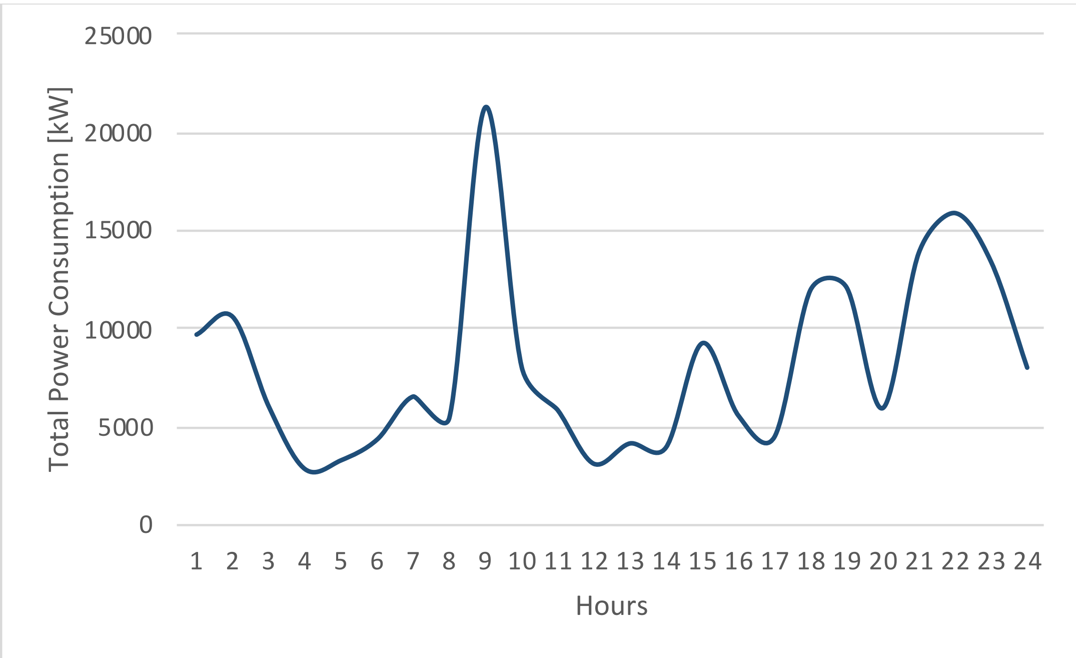


Los datos de generación de energía fotovoltaica para cada prosumidor quedan definidos en la siguiente figura, donde los prosumidores 6, 7 y 8 se asumen sin placas fotovoltaicas.

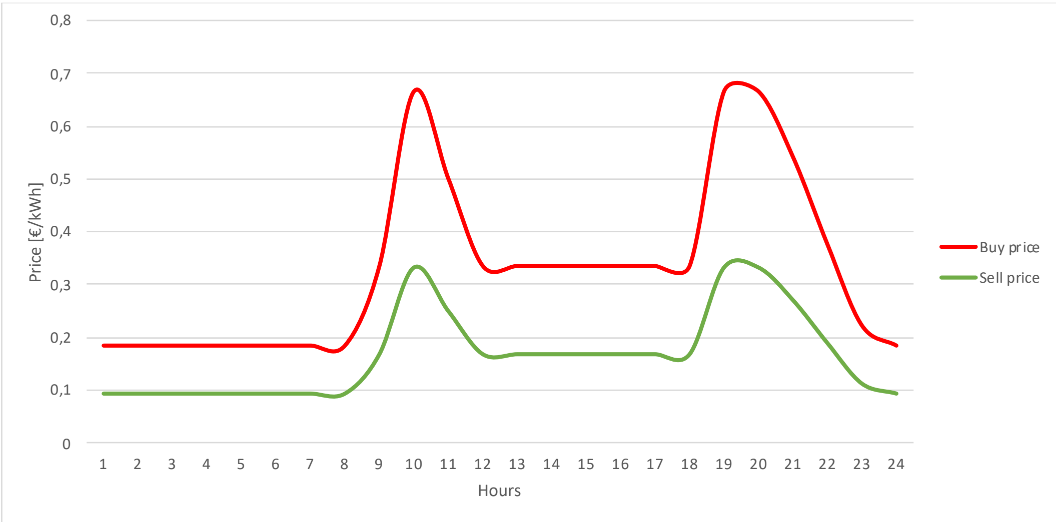


Tanto el consumo específico de cada prosumidor como el consumo global de la comunidad (en kW) se representan a continuación.





Los precios de compra y venta de energía quedan representados a continuación.



4. Resultados

Dados los siguientes conjuntos:

$$Nodos: \ I, \qquad with \ i \epsilon \{0, 1, 2, 3, 4, 5, 6, \dots, 11, 12, 13\}$$

$$Líneas: \ B, \qquad with \ b \epsilon \{1, 2, 3, 4, 5, 6, \dots, 12, 13, 14\}$$

$$Tiempo: \ T, \qquad with \ t \epsilon \{1, 2, 3, 4, \dots, 23, 24\}, \quad \Delta t = 1h$$

La siguiente función objetiva (OF) queda definida:

$$OF = min \sum_{t \epsilon T, i \, \epsilon I} ((price\_buy(t) * P_{buy\_user}(i,t) - price\_sell(t) * P_{sell\_user}(i,t)) * \Delta t)$$

donde $price\_buy(t)$ y $price\_sell(t)$ son los parámetros relacionados con los precios de compra/venta de energía en el tiempo. Con esta función, el objetivo es el de minimizar los costes globales de energía de la comunidad. Se asume que todos los prosumidores actúan en favor de la comunidad.

Dos casos son considerados

- CASO A: el modelo con los datos iniciales expresados anteriormente.

- CASO B: el modelo introduciendo paneles fotovoltaicos en los prosumidores 6, 7 y 8.

Tres situaciones son consideradas para cada caso: una LEC con intercambios internos y entre los diferentes puntos de alimentación, una LEC con puntos de alimentación de energía separados y una comunidad sin intercambios internos de energía.

Las restricciones expresadas previamente forzan el modelo a ejecutarse mediante una programación lineal de enteros mixtos, lo cual se realiza a través de CPLEX 20.1.0, la versión más reciente de 2021 del paquete de optimización lanzado al mercado por IBM (International Business Machines Corporation). La plataforma de optimización utilizada es AIMMS (Advance Interactive Multidimensional Modeling System).

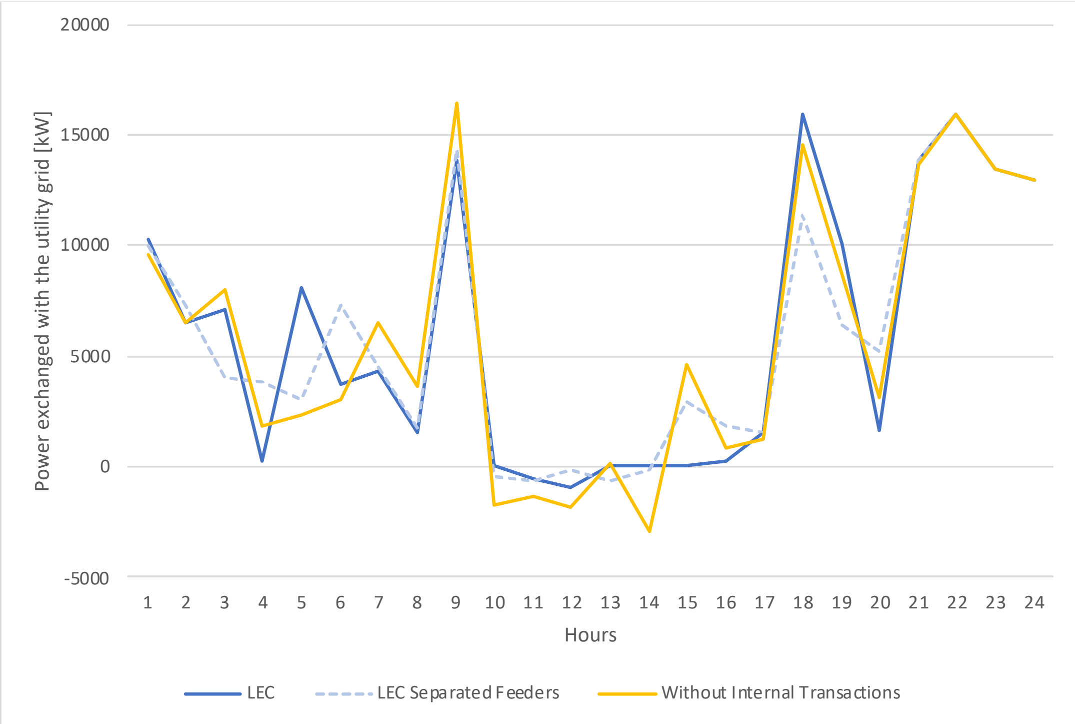
Los resultados de la función objetiva se expresan a continuación

CASE A	*OF (Euros)*	*Price difference w.r.t LEC (Euros/day)*
LEC	44.655,62	-
LEC with separated feeders	44.697,22	+ 41,6 ↑
No internal transactions	47.932,53	+ 3.276,91 ↑

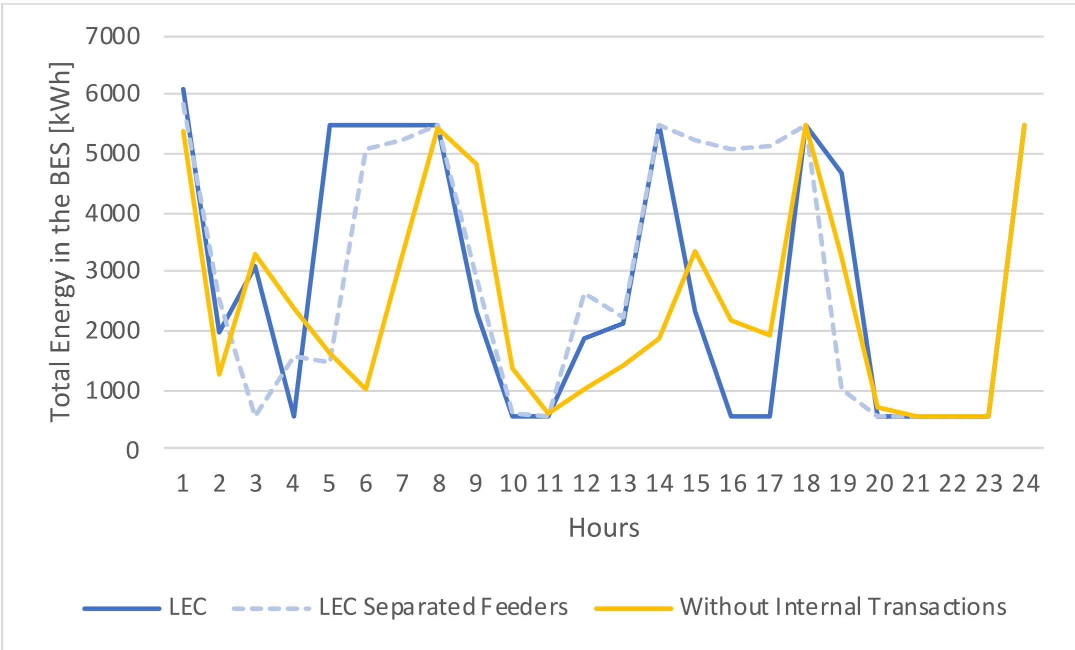
CASE B	*OF (Euros)*	*Price difference w.r.t LEC (Euros/day)*
LEC	41.292,06	-
LEC with separated feeders	41.293,53	+1,47 ↑
No internal transactions	44.071,18	+ 2.779,12 ↑

Comparando los resultados, se deduce que la introducción de una LEC es rentable. Además, el Caso B, donde se introducen placas fotovoltaicas, ofrece un mejor resultado para cualquier situación de comunidad.

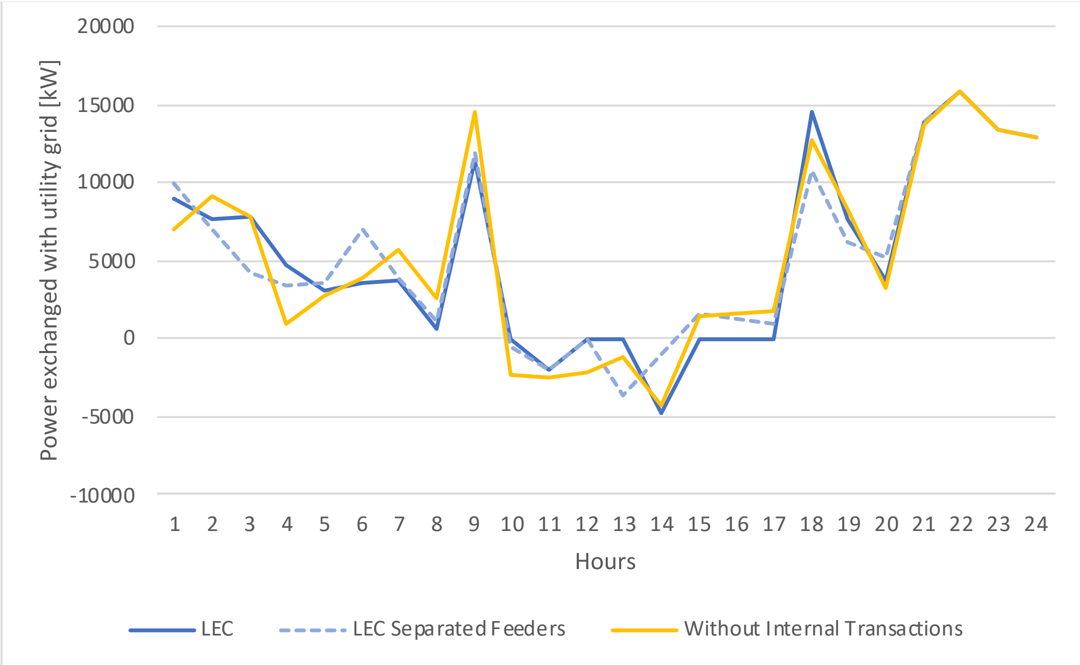
Un gráfico de la potencia intercambiada con la red pública en función del tiempo para el Caso A se observa a continuación.



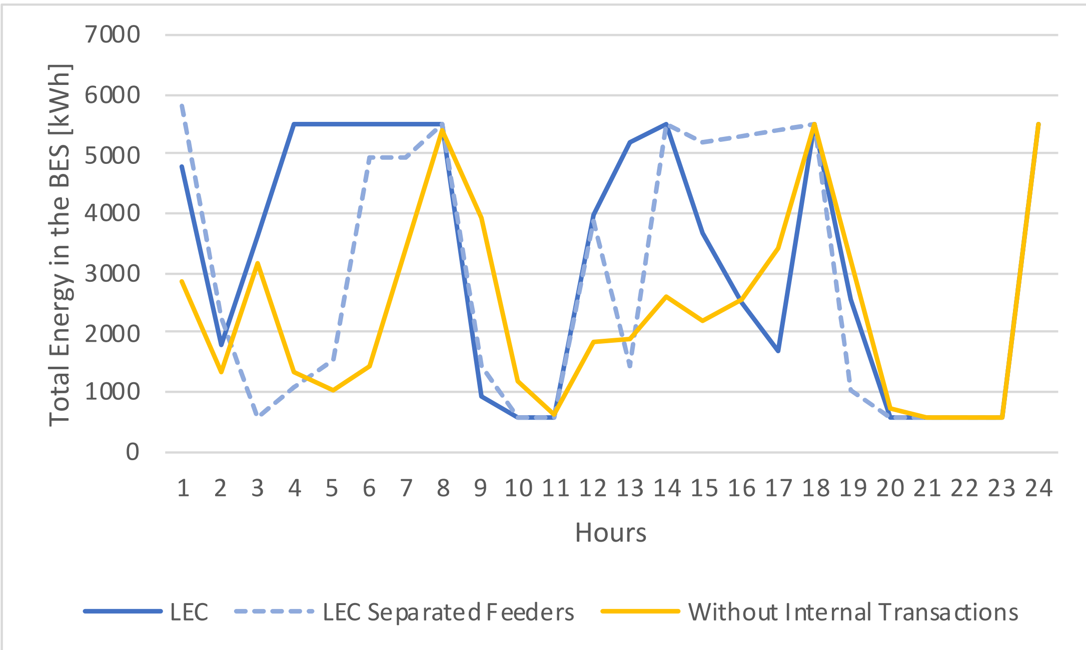
Un gráfico de la energía total en las baterías en función del tiempo para el Caso A se observa a continuación.



Un gráfico de la potencia intercambiada con la red pública para el Caso B se observa a continuación.



Un gráfico de la energía total en las baterías en función del tiempo para el Caso B se observa a continuación.



5. Conclusiones

En este Proyecto, la rentabilidad de una LEC sobre otro tipo de comunidades si transacciones internas queda demostrada. Aún así, un estudio personalizado de cada comunidad debe ser realizado de tal manera que los beneficios tanto de los prosumidores como de la comunidad en general queden optimizados, minimizando los conflictos de interés entre prosumidores.

En aras de la simplicidad, se ha utilizado una aproximación de corriente continua para mantener la linealidad de las restricciones. Permite una primera estimación de los flujos de potencia. Cabe recalcar que se necesita un modelo más redefinido para estimar adecuadamente las pérdidas de potencia.

APPLICATION OF OPTIMIZATION PROCEDURES TO THE PLANNING AND OPERATION OF LOCAL ENERGY COMMUNITIES

Author: García de Madariaga Orejas, Juan Bosco.
Supervisor: Borghetti, Alberto.
Collaborating Entity: Università degli Studi di Bologna

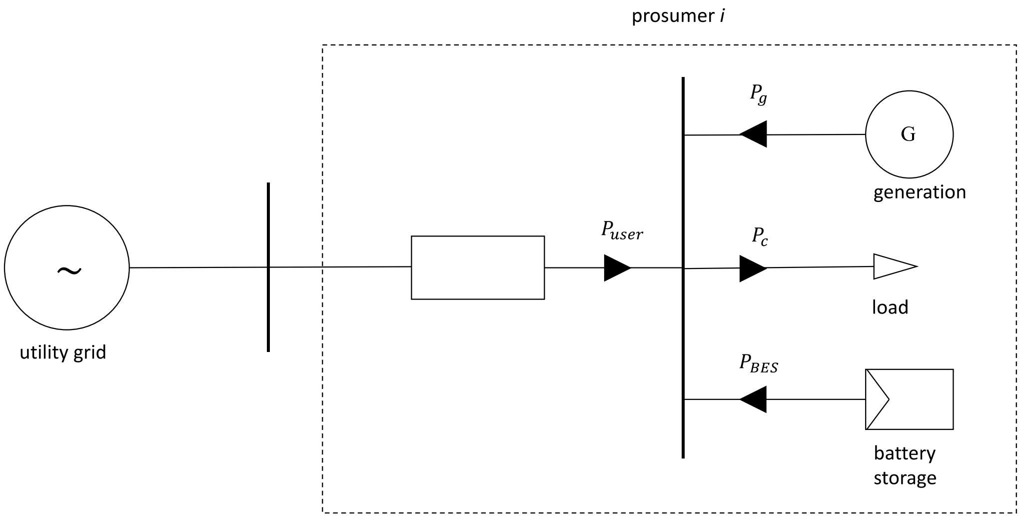
ABSTRACT

1. Introduction

In this project, a study of a specific Local Energy Community (LEC) is carried out in such a way that its profitability can be verified in comparison with other communities without internal transactions. To achieve that, the total costs of the community of energy distribution with the utility grid are minimized through an optimization procedure on a day (24 hours).

2. Model Constraints

In our specific LEC, each prosumer (a consumer and producer at the same time) is assumed to have a PV generation, a load, and a battery storage. Losses are neglected for the sake of simplicity.



Each prosumer is constrained by:

$$P_{user} = P_c - P_g - P_{BES}$$

where positive directions are assumed as in the figure shown above. Reactive power is neglected as we assume a DC simplified model of power flow, in order to obtain a simplified model for a first estimation of the flows.

The storage power P_{BES} of each prosumer is a control variable, defined by

$$P_{BES} = P_{BES}^{+} - P_{BES}^{-}$$

where P_{BES}^{+} and P_{BES}^{-} are nonnegative variables constrained by the maximum power limit of the battery. The battery charging and discharging losses can be neglected in comparison with the power distribution.

The energy level of each battery is defined by

$$E_t = E_{t-1} - (P_{BES,t} + \ell_{charge,t} + \ell_{discharge,t}) \cdot \Delta t$$

which is constrained to be between 10-100% of the battery capacity. The energy level at the beginning and at the end of the time horizon T is constrained to be equal to the initial battery capacity.

We define the variables P_{grid}, P_{buy_grid} and P_{sell_grid} in order to minimize costs of exchanges with the utility grid, constrained by:

$$P_{grid} = P_{buy\_grid} - P_{sell\_grid}$$

$$P_{user} = P^{+} - P^{-}$$

$$|P_{user}| = P^{+} + P^{-}$$

$$P_{buy\_grid} \leq P^{+}, \qquad P_{sell\_grid} \leq P^{-}$$

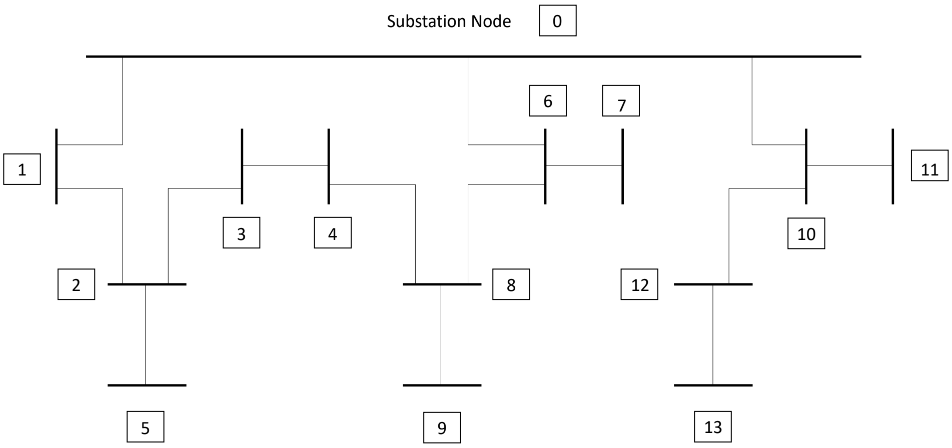
The DC power flow is represented by the following constraint:

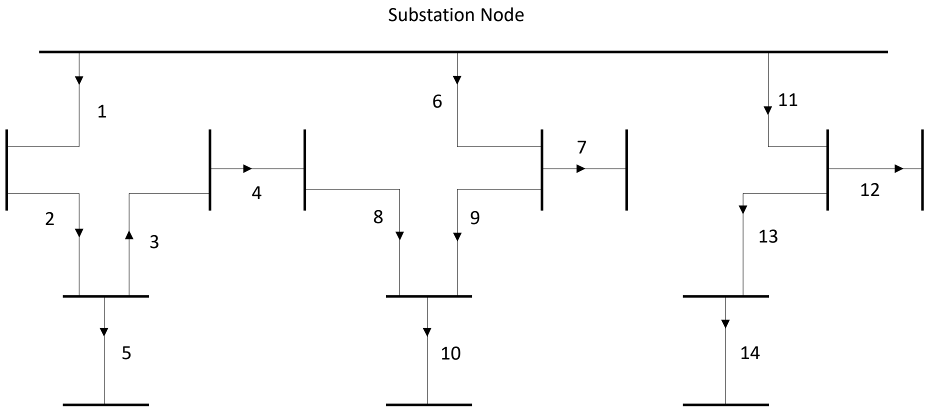
$$P_{km} = \frac{\theta_{km}}{x_{km}}$$

where θ_{km} represents the angle difference between nodes *k* and *m*, and x_{km} represents the branch reactance. The approximation assumes the resistance negligible with respect to the reactance for each branch. The model is also constrained by the equilibrium of entering and exiting power.

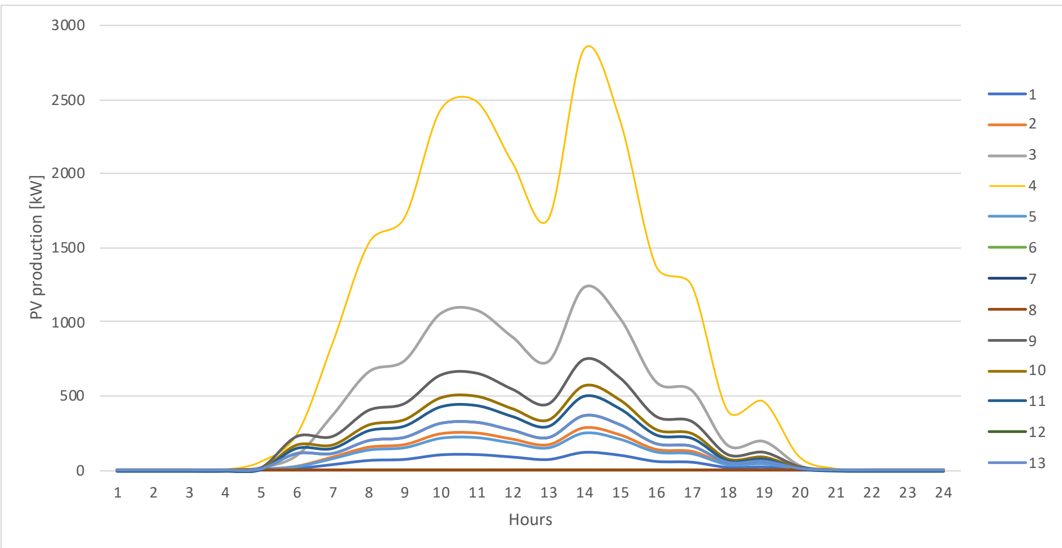
3. Model Description and Data

The specific LEC in this project is assumed to have fourteen nodes, where one node represents the utility grid and the other thirteen represent the prosumers. Fourteen branches define the complete community.



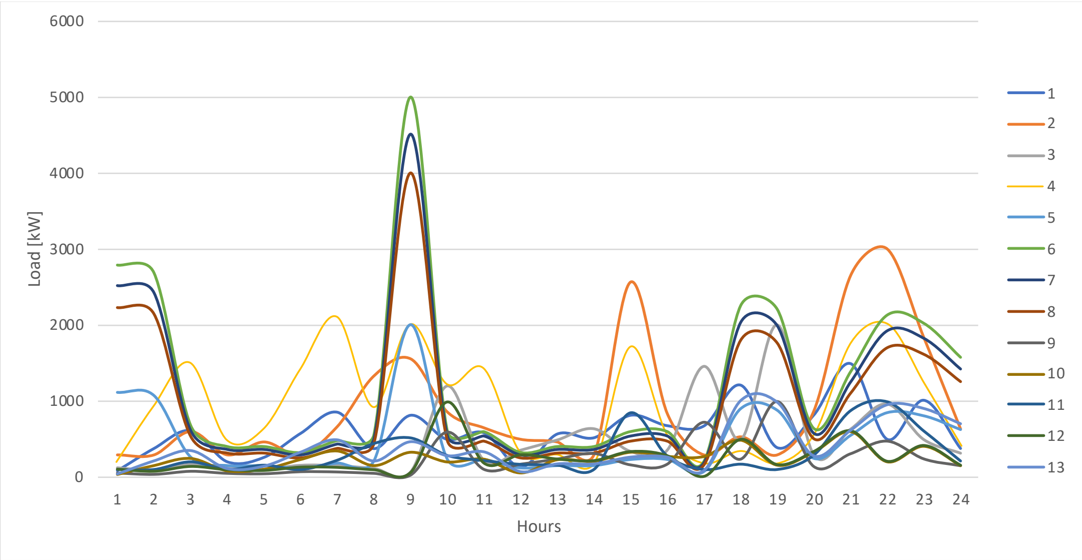


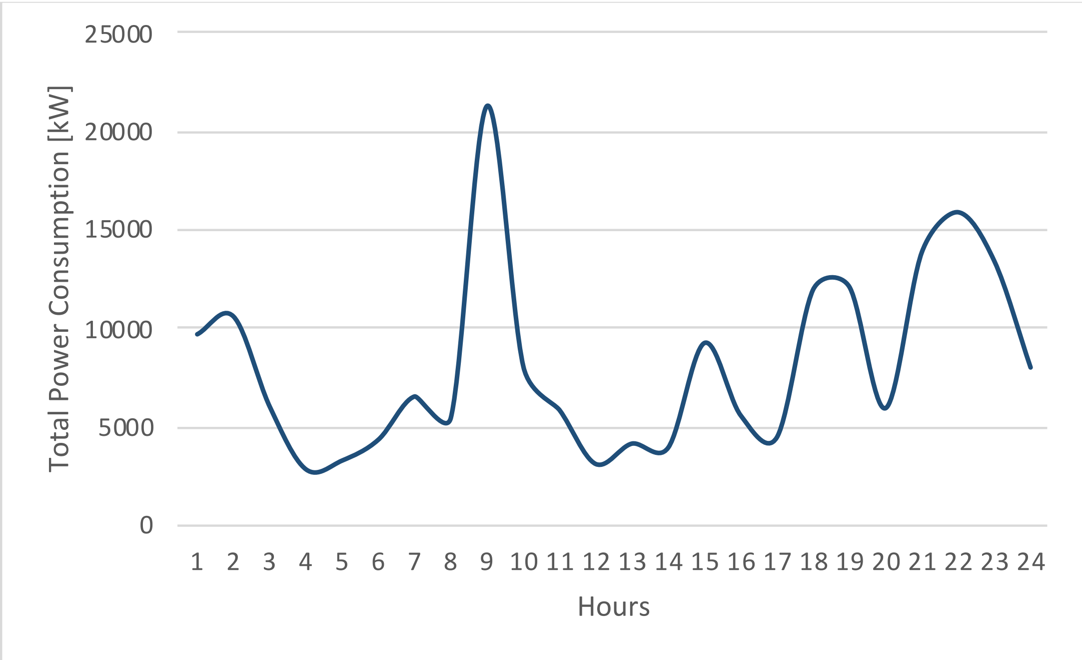
The data regarding the PV generation for the base case is represented in the following figure in time domain.



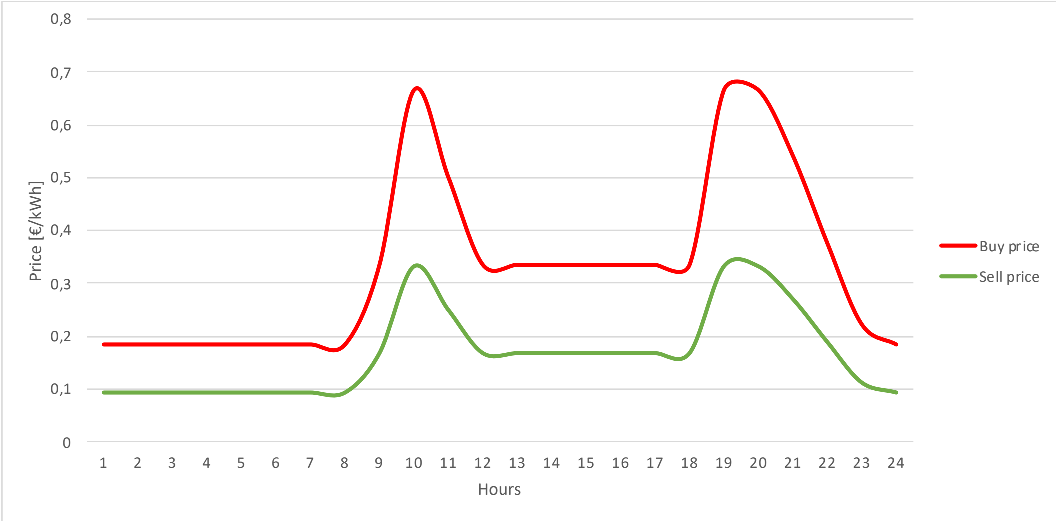
where prosumers 6,7 and 8 are assumed not to have PV panels for the base case.

Both the specific loads of each prosumer and the global load of the community are represented in the following figures in time domain, respectively.





The buying and selling prices of power exchanges with the utility grid are represented in the following figure.



4. Objective Function and Results

Given the following sets:

$$Nodes:\ I, \qquad with\ i\epsilon\{0,1,2,3,4,5,6,\dots,11,12,13\}$$

$$Branches:\ B, \qquad with\ b\epsilon\{1,2,3,4,5,6,\dots,12,13,14\}$$

$$Time:\ T, \qquad with\ t\epsilon\{1,2,3,4,\dots,23,24\}, \quad \Delta t = 1h$$

the following objective function is defined:

$$OF = min \sum_{t\epsilon T, i\ \epsilon I} ((price\_buy(t) * P_{buy\_user}(i,t) - price\_sell(t) * P_{sell\_user}(i,t)) * \Delta t)$$

where $price\_buy(t)$ and $price\_sell(t)$ are the parameters related to the price of the cost/sell operations at each time *t*. With this objective function the goal is the minimization of the energy costs of the community. All prosumers are assumed to act in favor of the community.

Two cases are considered:

- CASE A: the model with the base data as explained.

- CASE B: introduction of PV panels on prosumers 6, 7 and 8, so that they can generate PV energy.

Three situations are considered for each case: exchanges between the prosumers and between the different feeders as a LEC, a LEC with separated feeders and a community without internal transactions and separated feeders.

The constraints force the model to be a Mixed Integer Linear Programming type. The solver used is CPLEX 20.1.0, the most recent version on 2021 of the optimization solver package developed by IBM (International Business Machines Corporation). The platform used for the model execution is AIMMS (Advance Interactive Multidimensional Modeling System) Prescriptive Analytics Platform.

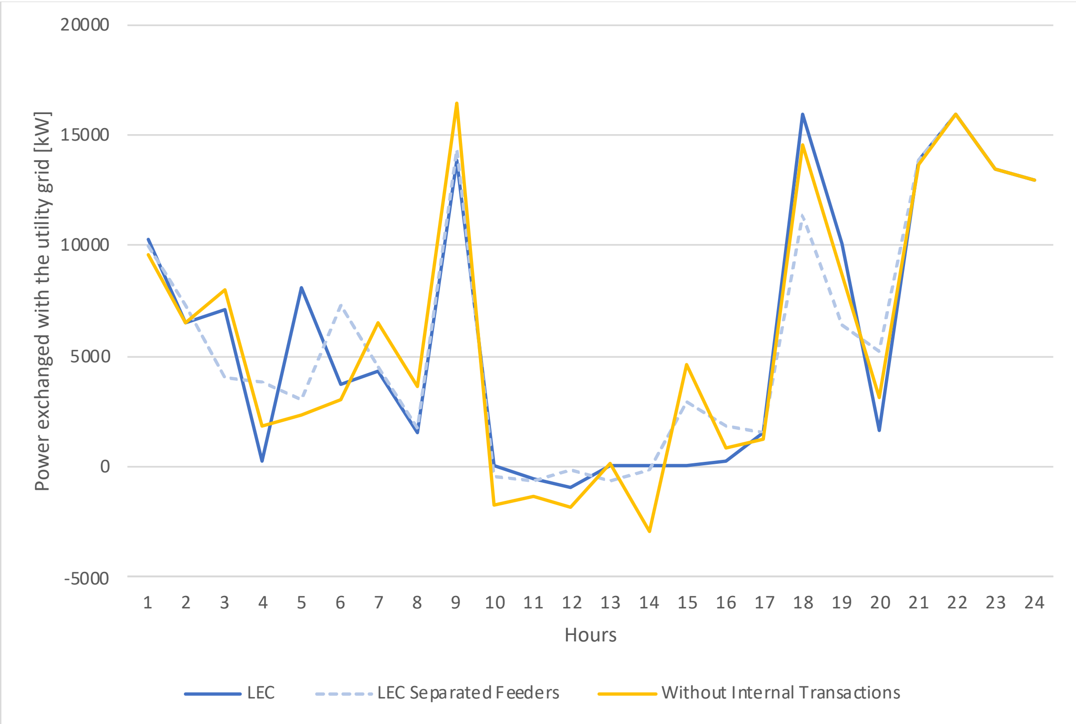
The OF results are expressed in the following tables.

CASE A	*OF (Euros)*	*Price difference w.r.t LEC (Euros/day)*
LEC	44.655,62	-
LEC with separated feeders	44.697,22	+ 41,6 ↑
No internal transactions	47.932,53	+ 3.276,91 ↑

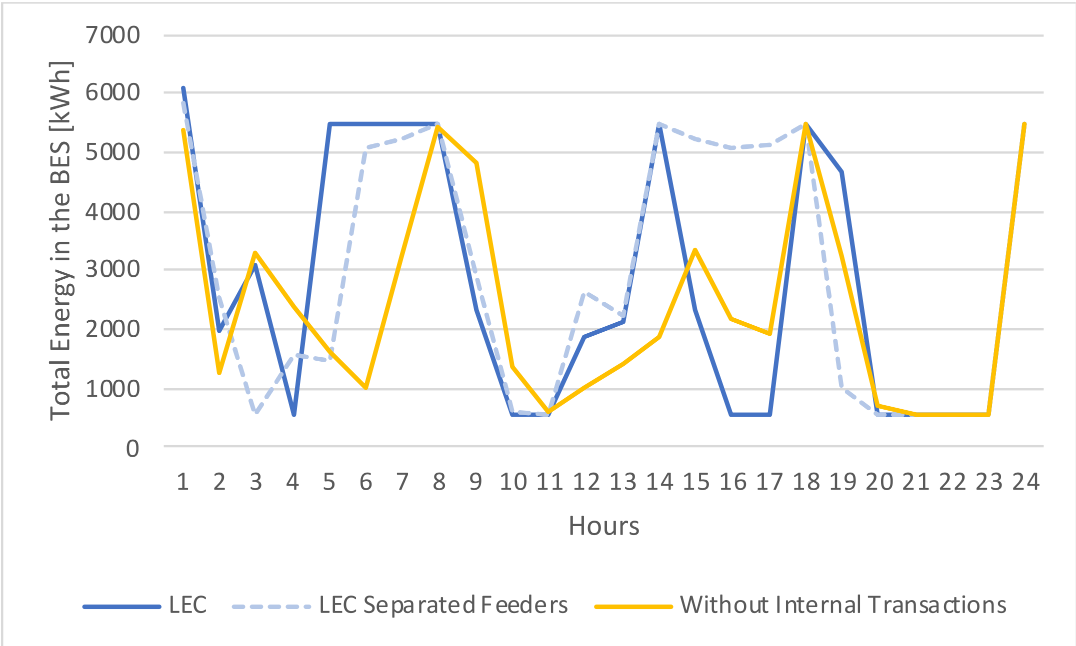
CASE B	*OF (Euros)*	*Price difference w.r.t LEC (Euros/day)*
LEC	41.292,06	-
LEC with separated feeders	41.293,53	+1,47 ↑
No internal transactions	44.071,18	+ 2.779,12 ↑

Comparing the OF results, it can be deduced that the introduction of a LEC favors the community costs. Also, the Case B appears to be more profitable than the Case A for any situation.

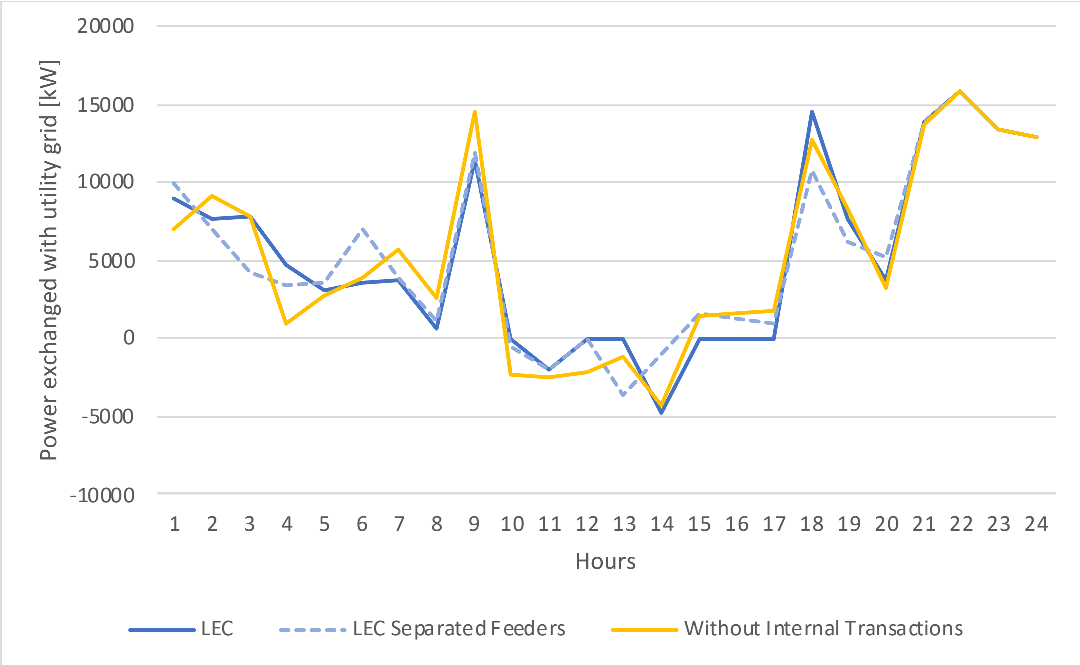
A graph regarding the exchanged power with the utility grid in time domain for the Case A is represented below.



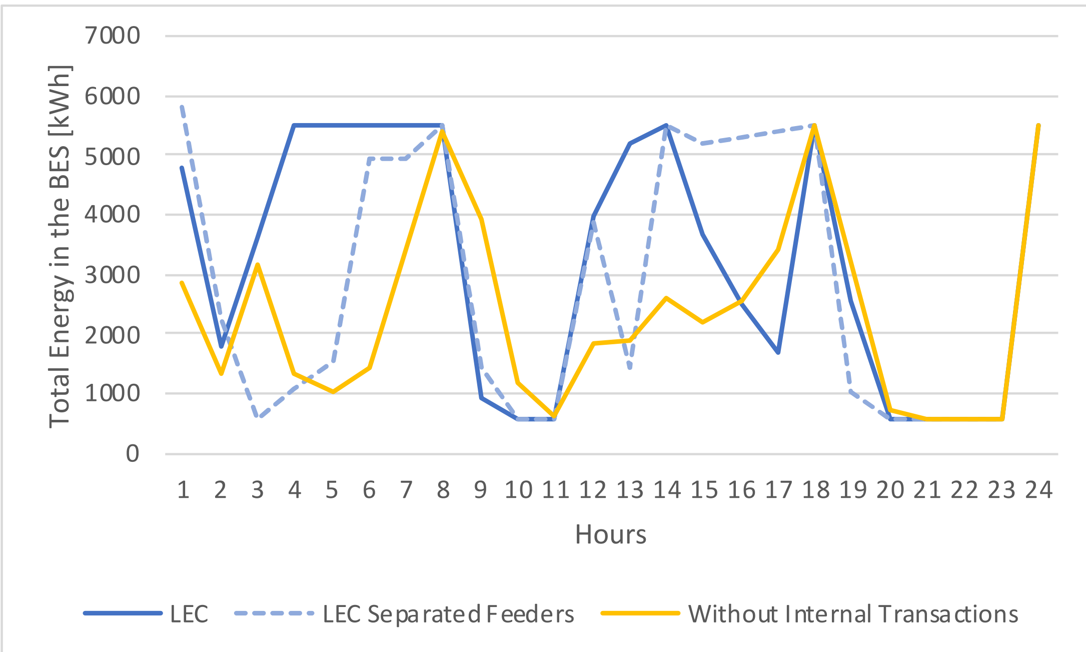
A graph regarding the total energy of the BES units in time domain for the Case A is represented below.



A graph regarding the exchanged power with the utility grid in time domain for the Case B is represented below.



A graph regarding the total energy of the BES units in time domain for the Case B is represented below.



5. Conclusions

In this project, the profitability of a LEC over other communities without internal transactions has been demonstrated.. However, an analysis of each community must be carried out in such a way that the benefits of prosumers and the community in general are optimized, so that the conflicts of interest between prosumers are minimal.

For the sake of simplicity, a DC approximation has been used in order to keep the linearity of the constraints. It allows a first estimation of the flows in the network. A more redefined model is needed in order to appropriately estimate the power losses in the feeders and voltage constraints.

Contents

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Abbreviations List

LEC: Local Energy Community

LECs: Local Energy Communities

PV: Photovoltaic

LCOE: Levelized Cost of Electricity

BOS: Balance of System

MILP: Mixed Integer Linear Programming

OF: Objective Function

AIMMS: Advanced Interactive Multidimensional Modeling System

1 INTRODUCTION AND DESCRIPTION OF THE PROJECT

1.1. INTRODUCTION TO LOCAL ENERGY COMMUNITIES

A Local Energy Community (LEC) is an open and voluntary legal entity in which the main objective is to achieve energetic benefits. These communities encourage shared self-consumption through the use of renewable energy. The community is made up of a group of prosumers (consumers and producers at the same time), each of which can have energy storage, generators and loads.

The main objective of LECs is to achieve an optimal distribution of the electricity by controlling the share of electrical energy between the prosumers and the utility grid, in such a way that both the global costs and losses of the community are minimized.

The difference between a LEC and a distribution network can be understood by referring to the definition of a microgrid, which can be defined as a small part of a smart grid and its main characteristic is the availability to control the energy distribution. The main peculiarity that differences a LEC from a microgrid is the interaction between prosumers in relation with energy distribution.

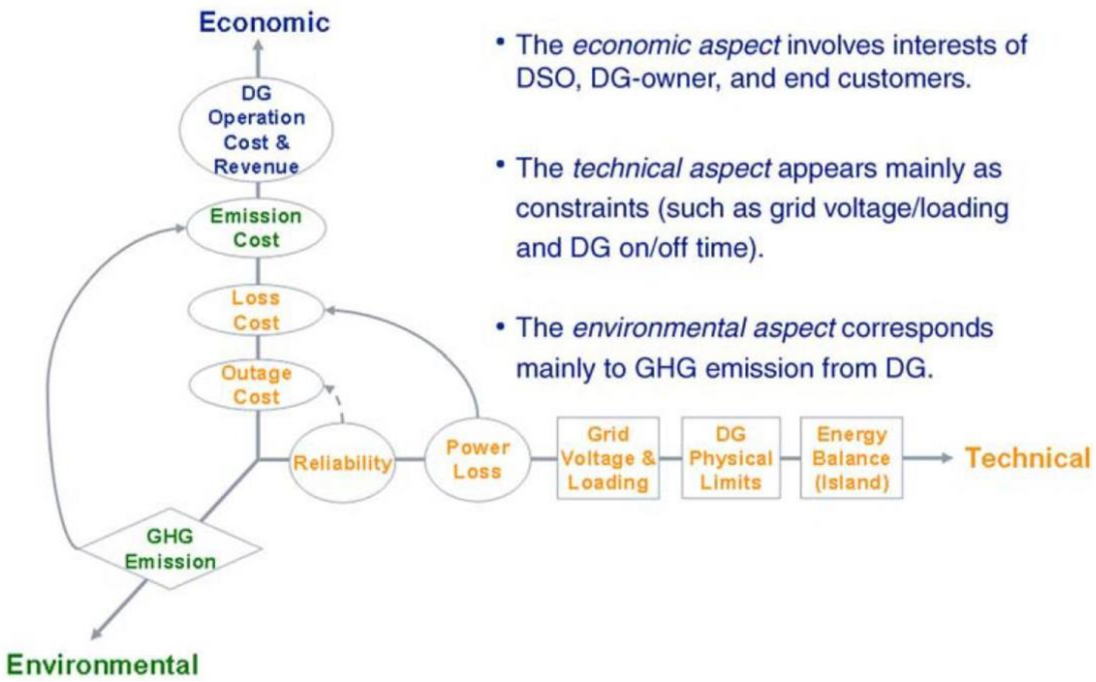

Figure 1. Microgrid operation strategies [1].

The above statements are reflected in the following representative example. We consider a prosumer with PV panels on its roof, represented in *Figure 2* as Prosumer A, in such a way that its energy production in a certain time is higher than its demand. Then, we consider a prosumer with a large daily demand, represented in *Figure 2* as Prosumer B.

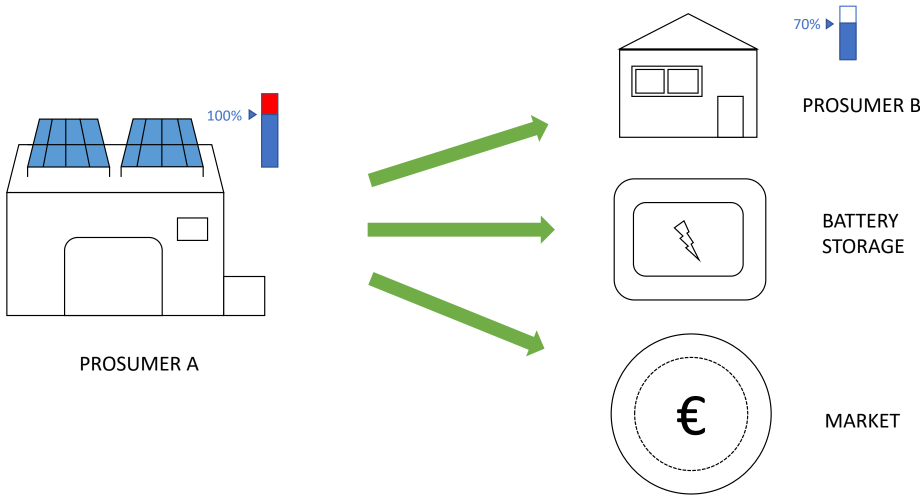

Figure 2. Representative example of the possibilities of energy distribution in a LEC.

As it is shown in the *Figure 2*, in a LEC the excess energy produced by A could be either distributed to B, stored in a battery for later use or redistributed on the market. Any combination is possible if the power flow allows it.

1.2. OBJECTIVE OF THE PROJECT

The objective of this project is to minimize the daily power losses of a certain LEC through the AIMMS Prescriptive Analytics Platform, analyze the results and extrapolate them to obtain conclusions. The results are obtained by applying the Gurobi Optimizer, which is an optimization programming solver, on AIMMS.

In addition, information about PV panels and their economic, social, and environmental impacts will be put into perspective in comparison to other power generation methods.

For the sake of simplicity, a DC approximation has been used in order to keep the linearity of the constraints. It allows a first estimation of the flows in the network. A more redefined model is needed in order to appropriately estimate the power losses in the feeders and voltage constraints.

1.3. *EQUATIONS AND ASSUMPTIONS*

The aim of this chapter is to introduce some equations and assumptions needed to constraint the programming model.

1.3.1. *POWER LOSSES IN TRANSMISSION NETWORKS*

The LEC is a set of transmission lines, where electrical losses are caused by the corona discharge on the conductor and the impedances of each line. The corona discharge losses are expected to be small. Due to the complexity of the design, neglecting these losses simplifies the calculations, obtaining a quite reliable result.

In order to illustrate a transmission line, we consider the π-model represented on *Figure 3.*; in which k and m are the nodes of the line, V_k and V_m are their respective voltages, I_{km} and I_{mk} are the currents entering the respective nodes, Y_{km} is the series admittance and Y_{km}^{sh} is the shunt admittance.

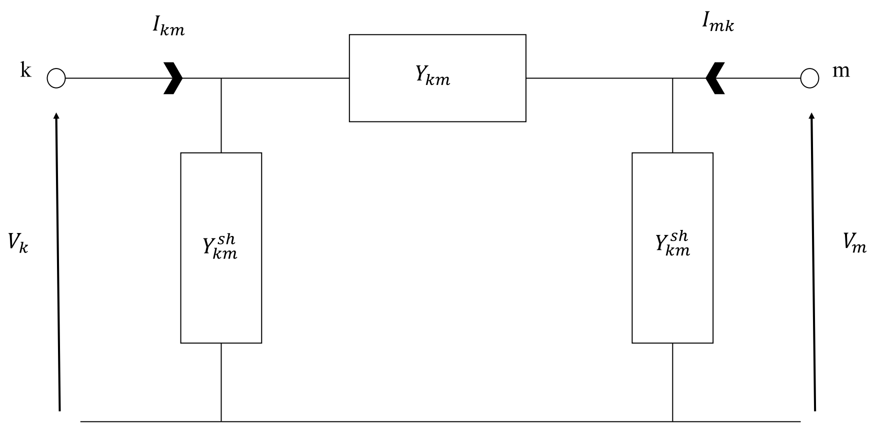

Figure 3. π-model of a transmission line

The equations of the complex power flowing through the line from each node are represented as

$$S_{km} = P_{km} + j \cdot Q_{km} = V_k \cdot I_{km}^*$$

$$S_{mk} = P_{mk} + j \cdot Q_{mk} = V_m \cdot I_{mk}^*$$

where P_{km} is the respective active power, Q_{km} is the reactive power, and I_{km}^* is the conjugate of the current entering the k node. The nomenclature applies in the same way for node m.

The currents are defined as

$$I_{km} = \left(Y_{km}^{sh} + Y_{km}\right) \cdot V_k - Y_{km} \cdot V_m$$

$$I_{mk} = \left(Y_{km}^{sh} + Y_{km}\right) \cdot V_m - Y_{km} \cdot V_k$$

The power losses are given by

$$P_{loss} = P_{km} + P_{mk} = g_{km} \cdot (|V_k|^2 + |V_m|^2 - 2 \cdot |V_k| \cdot |V_m| \cdot \cos \theta_{km})$$

$$Q_{loss} = Q_{km} + Q_{mk}$$

$$Q_{loss} = -b_{km} \cdot (|V_k|^2 + |V_m|^2 - 2 \cdot |V_k| \cdot |V_m| \cdot \cos \theta_{km}) - b_{km}^{sh} \cdot (|V_k|^2 + |V_m|^2)$$

where g_{km} is the real part of Y_{km} , b_{km} is the imaginary part of Y_{km} , b_{km}^{sh} is the imaginary part of Y_{km}^{sh} and θ_{km} is the angle difference between V_k and V_m.

The power loss calculation could be approximated by different power flow methods in order to reduce the programming code.

1.3.2. DC POWER FLOW APPROXIMATION

This approximation is used in order to achieve a fast solution of the power flow of an electric power system.

The approximations are such that both the series resistance and the shunt admittance of the π-model represented on *Figure 3* are neglected. The voltage of each node is assumed to be 1 in per unit magnitude. The variation of the active power with the voltage phase angle is assumed linear, defined by

$$P_{km} = \frac{\theta_{km}}{x_{km}}$$

where P_{km} is the active power, x_{km} is the series reactance and θ_{km} is the phase angle difference between nodes *k* and *m*.

The approximation assumes the resistance negligible with respect to the reactance for each branch. For the case of medium voltage networks, the values of the resistances are analogous to the values of the reactances. In low voltage feeders, the value of the resistance is higher thant the value of the reactance.

1.4. MODEL DESCRIPTION AND CONSTRAINTS

In the model, we consider a LEC made up of several prosumers and a utility grid. We consider a set of prosumers (*i* prosumers in a set *I*) and a set of time intervals (*t* time intervals in a set *T*). As a daily optimization is assumed, the time horizon is 24 hours.

Each prosumer has generation, load and energy storage. The net power of each prosumer is given by

$$P_{user} = P_c - P_g - P_{BES}$$

$$Q_{user} = Q_c - Q_g$$

where P_c and Q_c are the active and reactive power consumption of the load, P_g and Q_g are the active and reactive generation power and P_{BES} is the storage power, considered positive if provided by the battery. In this model, the PV production is assumed to operate at unity power factor ($Q_g = 0$).

In order to illustrate each prosumer set, we consider the model represented in *Figure 4* and *Figure 5*. All prosumers are assumed to act on behalf of the community.

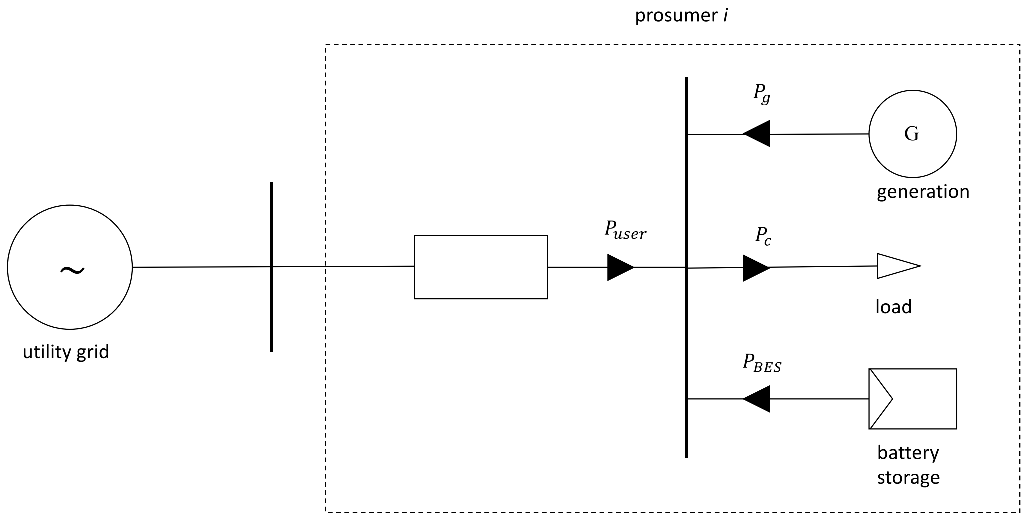

Figure 4. Prosumer set representation.

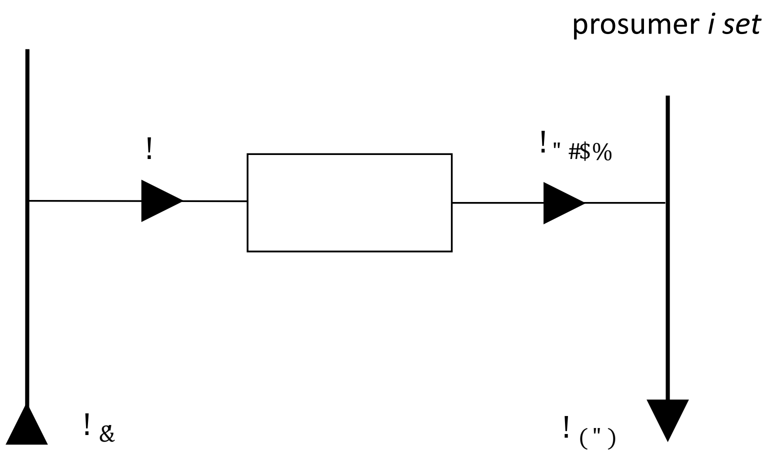

Figure 5. Power flow in a prosumer set.

where P_{in} and P_{out} are the power entering and exiting the prosumer set, respectively. The power losses regarding the branch impedance are assumed equal on all prosumers and can be neglected.

The charging and discharging operation losses of the battery are given by

$$\ell_{charge} = (1 - \eta_{charge}) \cdot P_{BES}^{-}$$

$$\ell_{discharge} = \left(\frac{1}{\eta_{discharge}} - 1\right) \cdot P_{BES}^{+}$$

where P_{BES}^{+} and P_{BES}^{-} are nonnegative variables constrained by the maximum power limit of the battery. The battery charging and discharging losses can be neglected in comparison with the power distribution.

The storage power P_{BES} of each prosumer is a control variable, defined by

$$P_{BES} = P_{BES}^{+} - P_{BES}^{-}$$

The energy level of each battery is defined by

$$E_t = E_{t-1} - (P_{BES,t} + \ell_{charge,t} + \ell_{discharge,t}) \cdot \Delta t$$

which is constrained to be between 10-100% of the battery capacity. The energy level at the beginning and at the end of the time horizon T is constrained to be equal to the initial battery capacity.

We define the variables P_{grid}, P_{buy_grid} and P_{sell_grid} in order to minimize costs of exchanges with the utility grid, constrained by:

$$P_{grid} = P_{buy\_grid} - P_{sell\_grid}$$

$$P_{user} = P^{+} - P^{-}$$

Equation 1: $$|P_{user}| = P^{+} + P^{-}$$

$$P_{buy\_grid} \leq P^{+}, \qquad P_{sell\_grid} \leq P^{-}$$

The Mixed Integer Linear Programming solver is more efficient than the nonconvex solver. In order to force the model to be linear, the *Equation 1* must be redefined with an indicator variable *w* as follows:

1. Definition of the indicator variable

$$w \ \ binary$$

2. Indicator constraint

$$P_{user} = P^{+} + P^{-} \qquad if\ w = 1$$

$$-P_{user} = P^{+} + P^{-} \qquad if\ w = 0$$

The DC power flow approximation, explained in *Chapter 1.3.2*, is used to constraint the power flow of the system. Furthermore, the balancing constraints of input and output power on each node must be introduced, as defined on *Chapter 3*.

The constraints shown in this chapter are assumed from [2] and developed for this specific project.

2 SUSTAINABLE TECHNOLOGIES

The aim of this chapter is to deepen the technologies used in LECs, highlighting those that have a lower impact, and comparing them with other energy generation methods.

Sustainability in energy generation can be defined as thriving in energy technologies without compromising future generations, considering a social, an economic and an environmental sphere.

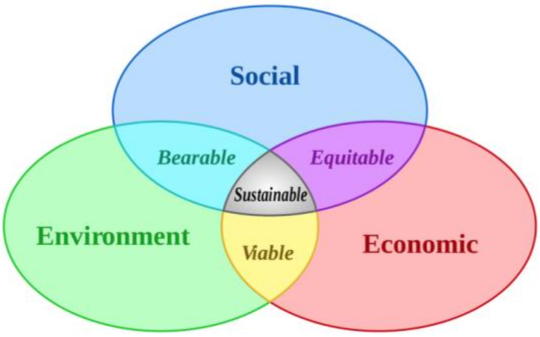

Figure 6. Sustainability diagram. Retrieved from Wikipedia.

2.1 ENERGY IMPACT IN EUROPE AND EUROPEAN COMMISSION RECOMMENDATIONS

The reason behind the recent emergence of the LECs in Europe is the convenience to give citizens responsibility on the energy market future, in particular to achieve the decarbonization targets for 2050 established by the European Commission. The objective of the European Commission is to reach zero net greenhouse gas emissions by 2050, in a profitable and fair way. As it can be seen in *Figure 7*, each European region has different climate change impacts and, thus, the purposes must be different depending on their circumstances.

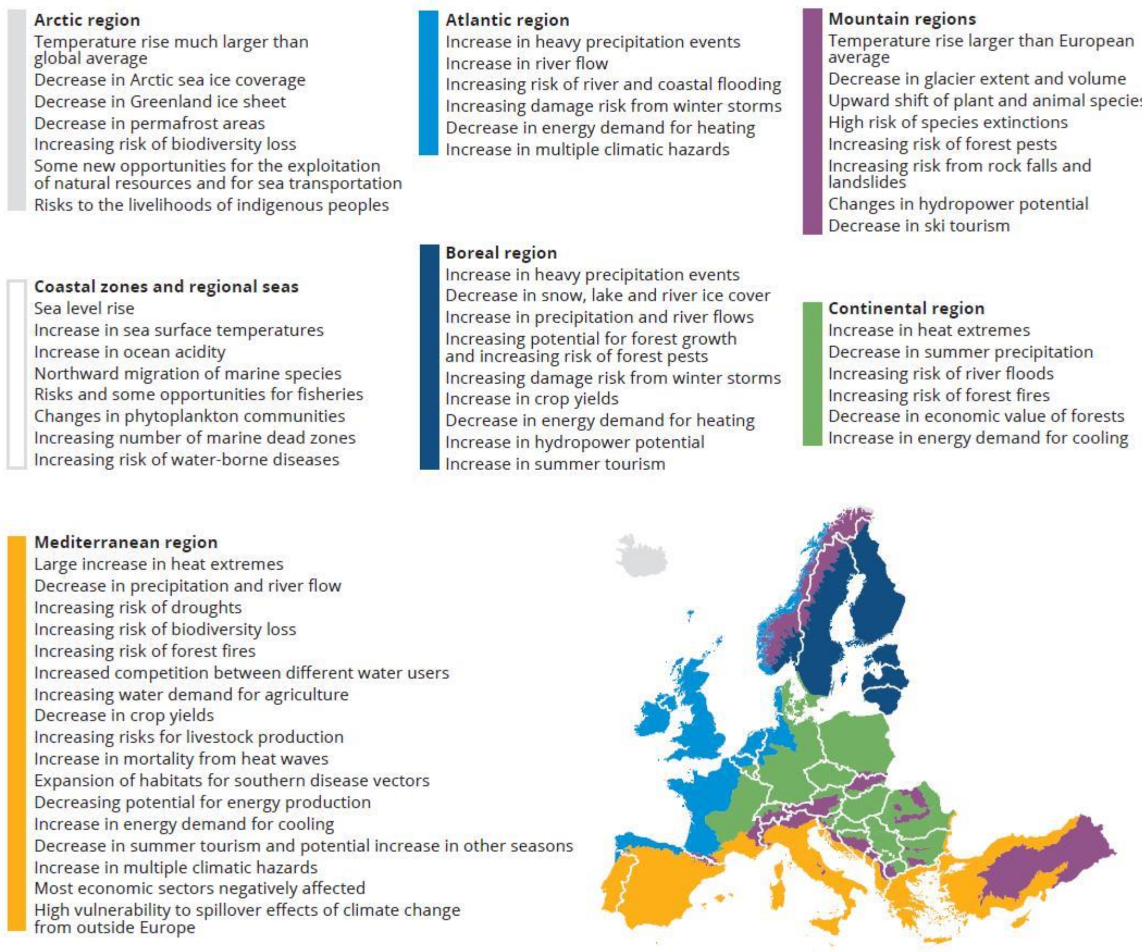

Figure 7. Climate change impacts in Europe [3].

As the European Commission communicated in 2018: "The share of renewable energy in final energy consumption increased from 9% in 2005 to 17% today" [3]. In the aforementioned paper, the increase in energy efficiency and the increase in the consumption of renewable energies are considered as the main energy objectives. This trend towards greater dependence on renewable energy favors the emergence of LECs.

In order to achieve the planned objectives, the European Commission establishes seven key strategic plans. Among them, those that can be strengthened through an increase in LECs are:

- "Maximize the deployment of renewables and the use of electricity to fully decarbonize Europe's energy supply" [3].

- "Develop an adequate smart network infrastructure and inter-connections" [3].

In conclusion, encouraging the emergence of new LECs as protagonists in the energy market results in an optimization of energy use and a reduction in the negative impacts of energy generation on the environment.

2.2 SOCIAL, ECONOMIC AND ENVIRONMENTAL ANALYSIS ON ELECTRICAL ENERGY GENERATION

Regarding electrical energy, energy is obtained from the transformation of other types of energy using alternators or generators. Thermoelectric, hydroelectric, wind, photovoltaic or tidal energy generation can be differentiated. This chapter consists of a brief analysis of the differences between electrical energy generation methods in relation to social, environmental, and economic impact.

The emerging shift towards the use of renewable energies is since they produce zero CO_2 emissions.

As stated by the director of APPA (Spanish Association of Renewable Energy Companies, González Moyá): "Solar photovoltaic is the one that is called to lead the electric revolution, hand in hand with wind power, as it is already the most competitive source of energy for the generation of electricity, both among renewable and non-renewable energy sources". In this way, the focus of this subchapter will be on PV generation.

Firstly, the socio-environmental sphere is analyzed. The noise produced by a PV panel is negligible, as they do not contain mechanically moving parts. The visual and land impact are minimal in comparison with other methods of generation since they can be installed both in remote places for global use, in order to reduce visual impact, and on the roof of particular homes for local generation, in order to reduce land use. Moreover, PV panels do not use water for energy generation and do not emit waste.

Figure 8. Solar panels installation on a house roof. Retrieved from Bloomberg.com.

A study of the German Aerospace Center (DLR) on a scenario for sustainable electricity [4] analyzes the socio-economic and environmental impact of the different electrical energy generation methods. In *Figure 9*, a graph regarding the costs per kWh of power generation of new power plants as a function of time (year) is represented. The new photovoltaic plants cost in said graph are assumed to be reduced exponentially (in a period from 2006 to 2050).

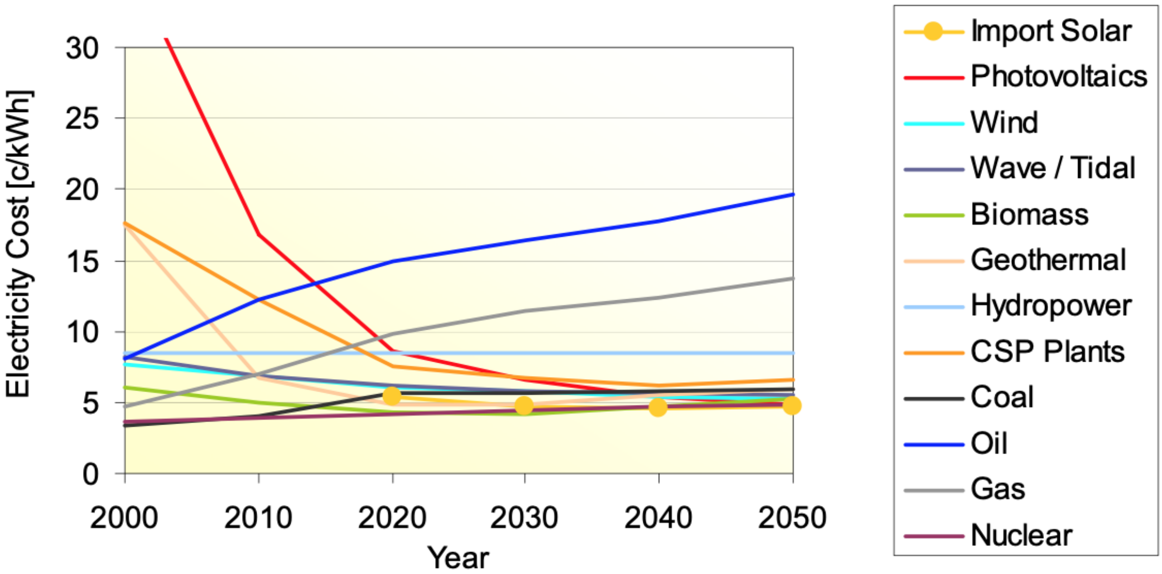

Figure 9. Electricity generation cost of new power plants (reported by DLR in 2006) [4].

The installation costs are one of the main economical drawbacks of the emergence of PV generation. However, a great cost reduction in time is estimated. Another economical drawback is the high costs of energy storage. However, new, more efficient, smaller, faster, and durable batteries are being developed.

In *Figure 10*, from the data of the Spanish Electrical Network, it can be deduced that a higher percentage of renewable energy takes place during daylight, due to the solar energy. For this reason, the evolution towards more efficient PV batteries is important.

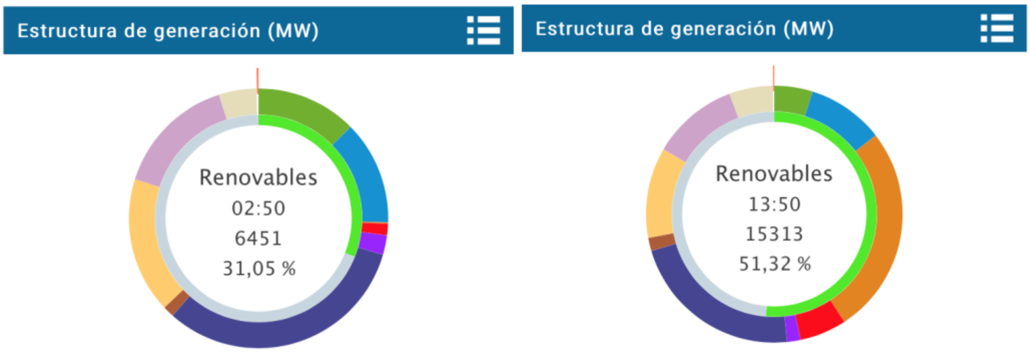

Figure 10. Renewable electrical energy generation on 02/08/2021 along the Iberian Peninsula. Left graph refers to 02:50h CEST time. Right graph refers to 13:50h CEST time. [5].

As stated by *Red Eléctrica Española*, on 28/12/2020 at 14:28 CEST, an 83% of the total electrical Iberian Peninsula demand was covered by renewable energy, which is a record percentage that shows the trend towards a renewable future.

A deeper analysis of the economic impact of solar panels can be made in reference to LCOE (Levelized Cost of Electricity) methodology, which is useful to determine the cost-effectiveness of different energy generation technologies, as stated in [6]. The assumptions made with this methodology are highly time dependent, as the PV costs are being dramatically reduced nowadays. The formula of the LCOE can be represented as follows:

$$LCOE = \frac{\sum_1^n IC_k + \sum_1^n OC_k}{\sum_1^n EP_k}$$

where IC_k are the investment and purchase costs on year *k*, OC_k are the operating costs on year *k*, and EP_k is the energy produced on year *k*.

The degradation process on PV panels must be considered, as it reduces their efficiency in time. In order to do that, service life must be introduced in the equation. The equation can be simplified as follows:

$$LCOE \approx \frac{IC}{EP_1} \cdot f(n;\varepsilon)$$

where IC is the total purchase price, EP_1 is the energy produced on the first year of operation and $f(n;\varepsilon)$ is a function dependent on the service life, n. More complex details on the meaning and development of this formula are approached in [6]. An assumption that can be extracted from this formula is that by decreasing the service life of the apparatus, its LCOE will decrease rapidly. However, a shorter service life is not always acceptable. For instance, at high values of IC the reduction of the service life in order to reduce the LCOE is not justified. In *Figure 11*, an estimation of PV panels lifetime is represented. As expected, the higher the degradation rate, the lower will the lifetime be.

Degradation rate	Lifetime to 80% P_{max} [years]	Lifetime to 50% P_{max} [years]
0.2%	100	250
0.5%	40	100
0.6%	33	83
0.7%	29	71
0.8%	25	63
1.0%	20	50

Figure 11. Estimation of the effect of degradation rate on system life of a PV panel [6].

After a certain time, close to their lifetime, PV panels must be substituted or refurbished. However, even for older PV panels the lifetime to 80% of maximum power is assumed to be higher than 20-25 years, as stated on [6]. Furthermore, this data was deduced in 2011, which suppose a cautious analysis for this study, with ten years gap of innovation.

Moreover, a greater increase on new installations of PV panels can be achieved by government incentives and technologic innovation. Also, the new emergence of electric cars can encourage the installation of PV panels in order to obtain electricity available for car charging stations on private or public parking.

The new PV technologies are being developed in order to minimize the total costs while maintaining high efficiency and long service life.

In summary, although the short-term costs of installing panels and batteries for the implementation of LECs may be high, in the long-term, and with the help of governments, it is not only profitable for each user due to the energy annual savings, but also environmentally positive for the planet and, hence, sustainable.

It should be considered that these analyses have been carried out for a project in the Mediterranean region, where the installation of photovoltaic panels is coherent.

2.3 PHOTOVOLTAIC STATE OF THE ART TECHNOLOGY

The aim of this subchapter is to deepen in the state-of-the-art photovoltaic technologies. The information regarding this subchapter is obtained from [7].

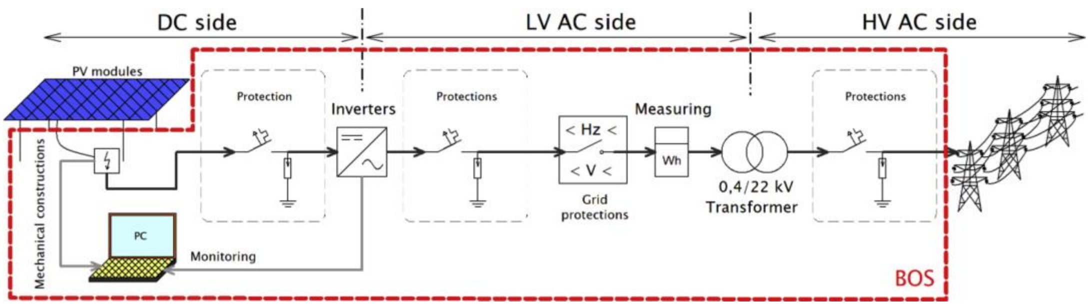

Figure 12. Simplified scheme of a PV system [7].

In *Figure 12*, a simplified scheme of a PV system is represented, where BOS stands for balance of system. With further assumptions made on the LCOE equation introduced on chapter 2.2., a cost decrease is obtained by increasing the PV module efficiency, while maintaining constant investment cost and service life.

$$EP_1 = A_m \cdot H_{sy} \cdot \eta_c \cdot \eta_m$$

A_m is the module area, H_{sy} is the yearly irradiation on the module surface, η_c is the converter efficiency and η_m is the module efficiency. A compromise between module efficiency and service life is reached when trying to reduce LCOE.

The development of new technologies can increase the PV module efficiency. As it is stated in [7], "improved module efficiency can be achieved by improving design and technology such as reducing optical losses (reducing reflectivity, reducing surface shaded contacts), reducing recombination losses (increasing material quality, reducing surface recombination) and reducing electrical losses (busbar optimization, reducing contact resistance)".

The state-of-the-art PV cells are made by crystalline silicon, as they provide high efficiency and long service life at relatively low costs.

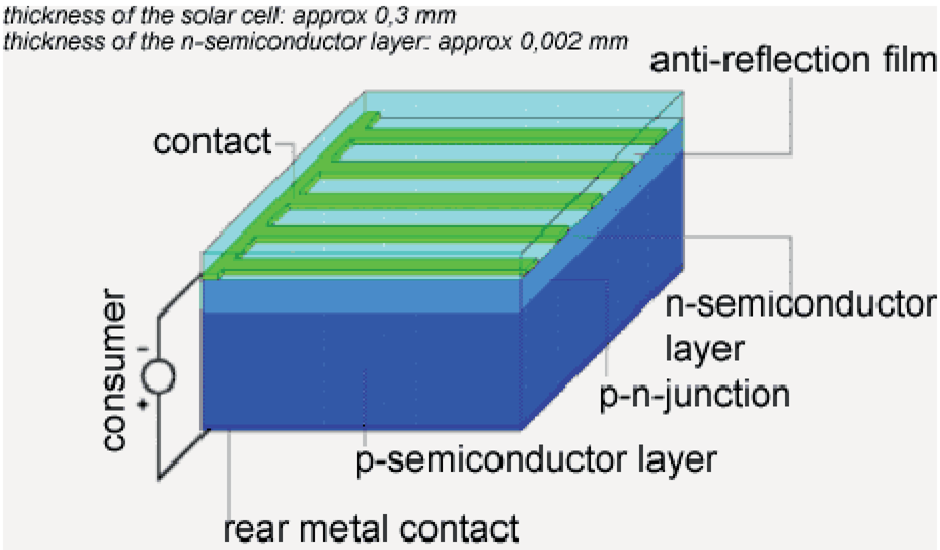

Figure 13. Schematic diagram of crystalline silicon PV cell [8].

The glass sheeting upon the PV module allows a greater life endurance in comparison with plastic sheeting. As stated in [7], "at the same time, the current cost of crystalline silicon modules is lower than the cost of modules from other materials due to the large-scale production of silicon feedstock, silicon ingots and wafers, silicon cells and modules". On the other hand, N-type or bifacial materials may happen to be the next technologies in favor of the PV development.

Lastly, it should be said that the increase on PV panels installations and technology development should be promoted by the governments through subsidies.

3 DESCRIPTION OF TECHNOLOGIES

The aim of this chapter is to introduce the technologies used to develop the optimization model.

The constraints introduced in *Chapter 1* force the model to be a Mixed Integer Linear Programming type. The MILP type allows to solve the programming model in which some variables are integer and other variables are non-integers. In our case, a binary variable has been introduced in order to redefine an absolute constraint into a linear constraint. In that way, our model is forced to be MILP type.

The platform used for the model execution is AIMMS (Advance Interactive Multidimensional Modeling System) Prescriptive Analytics Platform. As stated by Marcel Roelofs in the AIMMS user's guide, "The AIMMS Prescriptive Analytics Platform consists of an algebraic modeling language, an integrated development environment for both editing models and creating a graphical user interface around these models, and a graphical end-user environment". AIMMS supports lots of mathematical optimization problem types, among which is Mixed Integer Linear Programming, the one considered in this project.

AIMMS allows the user to develop any optimization problem in a simple and intuitive way thanks to its interface. Inside the Model Explorer window, there is a declaration tab where sets, parameters, variables, and more useful identifiers can be defined. Also, data can be either loaded or defined on the Main Execution window. In this way, the model becomes more intuitive and easier to follow. Furthermore, the data results can be transferred to excel for further analysis.

The solver used is CPLEX 20.1.0, the most recent version on 2021 of the optimization solver package developed by IBM (International Business Machines Corporation), which is able to solve MILP model type. CPLEX is able to solve linear programming problems by the simplex method, among other types.

4 OPTIMIZATION MODEL AND RESULTS

This chapter is the core of the project, in which the model of a LEC is introduced in order to optimize its energy distribution, present the results and analyze them.

4.1 LOCAL ENERGY COMMUNITY REPRESENTATION

The Local Energy Community to model in the optimization programming platform (AIMMS) is represented in *Figure 11* and *Figure 12*. This particular LEC has 14 nodes, in which the node *i=0* is the substation node, and 14 branches.

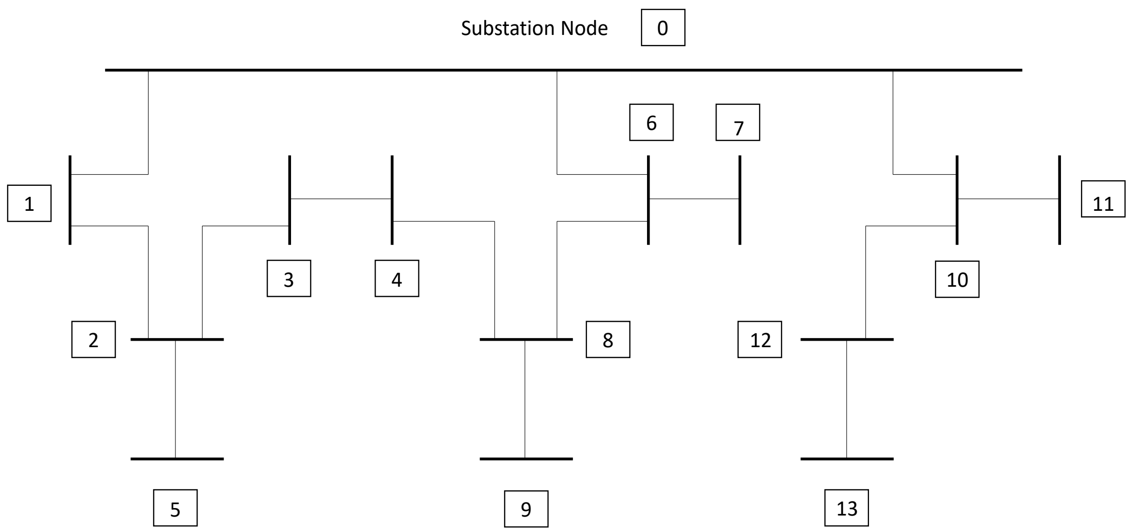

Figure 14. Local Energy Community representation to model on AIMMS. Nodes enumerated from 0 to 13.

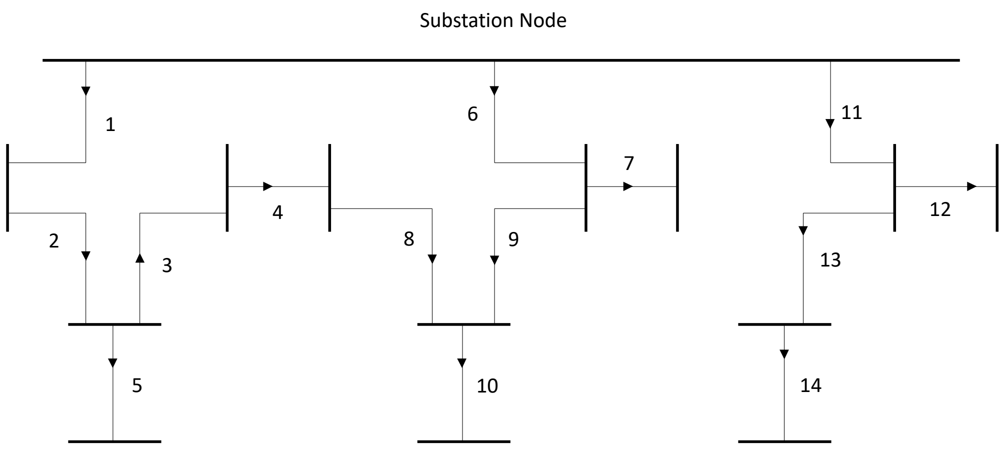

Figure 15. Local Energy Community representation to model on AIMMS. Branches enumerated from 1 to 14. The power flow positive directions are represented with arrows on the branches.

The balancing constraints of input and output power on each node with respect to the defined LEC on *Figure 12* are as follows:

$$P_{utility\_grid} = P_{flow\_01} + P_{flow\_06} + P_{flow\_010}$$

$$P_{flow\_01} = P_{flow\_12} + P_{grid}(1)$$

$$P_{flow\_12} = P_{flow\_23} + P_{grid}(2) + P_{flow\_25}$$

$$P_{flow\_23} = P_{flow\_34} + P_{grid}(3)$$

$$P_{flow\_34} = P_{grid}(4) + P_{flow\_48}$$

$$P_{flow\_25} = P_{grid}(5)$$

$$P_{flow\_48} = P_{grid}(8) + P_{flow\_89} - P_{flow\_68}$$

$$P_{flow\_89} = P_{grid}(9)$$

$$P_{flow\_06} = P_{grid}(6) + P_{flow\_67} + P_{flow\_68}$$

$$P_{flow\_67} = P_{grid}(7)$$

$$P_{flow\_010} = P_{grid}(10) + P_{flow\_1011} + P_{flow\_1012}$$

$$P_{flow\_1011} = P_{grid}(11)$$

$$P_{flow\_1012} = P_{grid}(12) + P_{flow\_1213}$$

$$P_{flow\_1213} = P_{grid}(13)$$

where $P_{utility\_grid}$ is the nonnegative variable that represents the power supplied by the utility grid at node i=0, and P_{flow_xy} is the power flow that exits node *x* and enters node *y*. The equations expressed above can be simplified as follows:

$$\sum_{x} P_{flow\_xi} = P_{grid}(i) + \sum_{z} P_{flow\_iz} \qquad \forall i$$

where *xi* are all the branches connecting nodes *x* with node *i*, and *iz* are all the branches connecting node *i* with nodes *z*. $P_{grid}(i)$ is the power entering each prosumer *i*.

The remaining constraints that define the optimization model are expressed in *Chapter 1.3*.

4.2 NUMERICAL DATA FOR THE PARAMETERS

The intention of this subchapter is to present in tables the numerical data assumed for every parameter introduced on AIMMS. All numerical data has been provided by my project director, Alberto Borghetti.

Regarding the DC power flow approximation assumed in *Chapter 1.3.2.*, the resistance and capacitance along the branches are neglected, and only the reactance is considered. The numerical values for the reactance along each branch *b* are given in *Table 1*.

Branch number, b	*Branch length* $[\boldsymbol{km}]$	*Reactance* $[\Omega/\boldsymbol{km}]$
1	1	0.529
2	1	0.5819
3	1	0.2116
4	1	0.47601
5	1	0.2116
6	1	0.5819
7	1	0.5819
8	1	0.5819
9	1	0.5819
10	1	0.47601
11	1	0.2116
12	1	0.5819
13	1	0.2116

14	1	0.47601

Table 1. Reactance numerical values across each branch.

The base values to operate in per unit magnitude are given by:

$$V_{base} = 23\ kV$$

$$P_{base} = 100\ kW$$

$$Z_{base} = \frac{V_{base}{}^2}{P_{base}}\ [\Omega]$$

where V_{base} is the base value for line to line voltages and P_{base} is the base value for three phase power.

The maximum capacity for the battery ratings are given in the following table.

Nodes, i	*Maximum Battery Capacity [kW]*
1	500
2	300
3	400
4	200
5	300
6	1000
7	500

8	1000
9	200
10	600
11	100
12	200
13	200

Table 2. Maximum battery capacities along each node (BES).

The numerical data of the PV generation for each node *i* and each time period *Δt* are given in *Table 3* and *Table 4*. Nodes 6, 7 and 8 are assumed not to have PV panels and, therefore, their PV power generation is null. The values are approximated in order to fit in the tables.

[kW]	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
i=1	0	0	0	0,044	2,419	10,61	37,67	66,84	74,45	106,1	108,5	90,45
i=2	0	0	0	0,102	5,529	24,26	86,11	152,7	170,2	242,5	248,1	206,7
i=3	0	0	0	0,448	24,19	106,1	376,7	668,4	744,5	1061	1085	904,5
i=4	0	0	0	1,024	55,29	242,6	861,1	1527	1701	2425	2480	2067
i=5	0	0	0	0,089	4,938	21,23	75,35	133,6	148,9	212,2	217,0	180,9
i=6	0	0	0	0	0	0	0	0	0	0	0	0
i=7	0	0	0	0	0	0	0	0	0	0	0	0

i=8	0	0	0	0	0	0	0	0	0	0	0	0
i=9	0	0	0	0,268	14,51	226,0	226,06	401,1	446,7	636,7	651,1	542,7
i=10	0	0	0	0,204	11,05	172,2	172,24	305,5	340,3	485,1	496,0	413,5
i=11	0	0	0	0,179	9,676	150,7	150,70	267,3	297,8	424,5	434,0	361,8
i=12	0	0	0	0,1344	7,257	113,03	113,03	200,5	223,3	318,3	325,5	271,3
i=13	0	0	0	0,1344	7,257	113,03	113,03	200,5	223,3	318,3	325,5	271,3

Table 3. Active PV power generation (in kW) of each node along the first 12 hours of one day. Columns correspond to time periods of Δt =1 hour from 00:00 to 12:00h. Rows correspond to nodes.

[kW]	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*
i=1	73,83	123,9	103,0	60,16	54,29	17,4	20,1	3,85	0,31	0	0	0
i=2	168,7	283,2	235,5	137,5	124,1	39,8	46,0	8,80	0,71	0	0	0
i=3	738,3	1239	1030	601,6	542,9	174	201	38,5	3,13	0	0	0
i=4	1687	2832	2355	1375	1241	398	460	88,0	7,16	0	0	0
i=5	147,6	247,8	206,0	120,3	108,5	34,8	40,3	7,70	0,62	0	0	0
i=6	0	0	0	0	0	0	0	0	0	0	0	0
i=7	0	0	0	0	0	0	0	0	0	0	0	0
i=8	0	0	0	0	0	0	0	0	0	0	0	0
i=9	442,9	743,5	618,2	360,9	325,7	104	120	23,1	1,88	0	0	0

i=10	337,5	566,4	471,0	275,0	248,2	79,6	92,1	17,6	1,43	0	0	0
i=11	295,3	495,6	412,1	240,6	217,1	69,7	80,6	15,4	1,25	0	0	0
i=12	221,4	371,7	309,1	180,5	162,8	52,2	60,4	11,5	0,94	0	0	0
i=13	221,4	371,7	309,1	180,5	162,8	52,2	60,4	11,5	0,94	0	0	0

Table 4. Active PV power generation (in kW) of each node along the last 12 hours of one day. Columns correspond to time periods of Δt =1 hour from 12:00 to 00:00h. Rows correspond to nodes.

The LEC is assumed to be in a Mediterranean region, where PV panels have an optimal operation. As it can be seen in the PV generation numerical data, the values are maximum in the region between 12:00 and 17:00h local times. A sunny/cloudless day is assumed.

The numerical data of the power consumption for each node *i* and each time period *Δt* are given in *Table 5* and *Table 6*. The values are approximated in order to fit in the tables.

[kW]	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
i=1	84,74	379,3	613,5	203,0	261	578,4	857,8	377,3	817,9	498,8	586,7	134
i=2	285,7	285,7	593,1	285,7	456	285,7	659,6	1326	1551	850,9	642,6	490
i=3	116,1	83,54	160,9	108,9	97,0	150,2	144,4	107,7	63,66	1196	214,4	349
i=4	207,4	928,6	1502	497,0	639	1416	2100	923,5	2002	1221	1426	329
i=5	1116	1074	270,5	160,0	160	129,2	192,2	222,5	2000	243,5	239,1	129
i=6	2790	2687	676,5	401,4	401	322,9	480,0	558,5	5000	608,6	597,6	322

i=7	2511	2418	608,8	361,5	361	290,6	432,0	502,3	4500	547,3	538,4	290
i=8	2232	2149	541,2	321,2	321	258,4	384,0	446,9	4000	487,1	478,3	258
i=9	58,07	41,77	80,58	54,44	48,9	75,12	72,46	53.52	32,66	598,2	107,4	174
i=10	33,89	151,7	245,4	81,22	104	231,4	343,3	150,9	327,0	199,5	234,7	53,8
i=11	95,23	95,23	197,7	95,23	152	94,4	219,6	442,1	517,0	283,3	214,2	163
i=12	97,08	69,83	134,5	91,05	81,8	125,5	121,1	89,45	54,85	1000	179,6	291
i=13	84,74	379,3	613,5	203,0	261	578,4	857,8	377,3	817,9	498,8	586,7	134

Table 5. Active power consumption (in kW) of each node along the first 12 hours of one day. Columns correspond to time periods of Δt =1 hour from 00:00 to 12:00h. Rows correspond to nodes.

[kW]	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*
i=1	570	521	817,8	679,8	676,6	1216	389,8	822	1500	499,6	1016	379,3
i=2	456	285	2563	830,7	285,7	524,4	285,7	864	2648	3000	1832	627,4
i=3	484	632	332,7	349,2	1454	483,3	2000	287	625,3	958,7	488,8	309,0
i=4	304	190	1712	554,9	190,8	350,6	190,8	577	1769	2004	1224	419,0
i=5	160	160	239,1	239,1	82,02	901,2	882,2	255	554,2	851,9	809,4	630,2
i=6	401	401	597,9	597,9	205,1	2253	2208	638	1385	2132	2023	1575
i=7	361	362	538,1	538,1	184,6	2027	1987	574	1246	1919	1821	1418

i=8	321	321	478,3	478,3	164,0	1802	1766	510	1108	1705	1618	1260
i=9	242	316	166,3	174,6	727,4	241,6	1000	143	312,5	479,3	244,4	154,4
i=10	228	208	327,1	271,9	270,6	486,5	155,9	329	600,0	199,8	406,5	151,7
i=11	152	95,5	854,4	276,9	95,23	164,9	95,23	288	882,0	1000	610,8	209,1
i=12	233	213	334,6	278,1	276,8	497,6	159,4	336	613,7	204,4	415,8	151,2
i=13	178	178	265,3	265,3	91,01	1000	980,1	283	614,7	946,4	898,1	699,3

Table 6. Active power consumption (in kW) of each node along the last 12 hours of one day. Columns correspond to time periods of Δt =1 hour from 12:00 to 00:00h. Rows correspond to nodes.

An example of power demand on a Mediterranean region (Iberian Peninsula) can be observed in *Figure 13* and *Figure 14*, in order to better comprehend the peak values on daily power consumption.

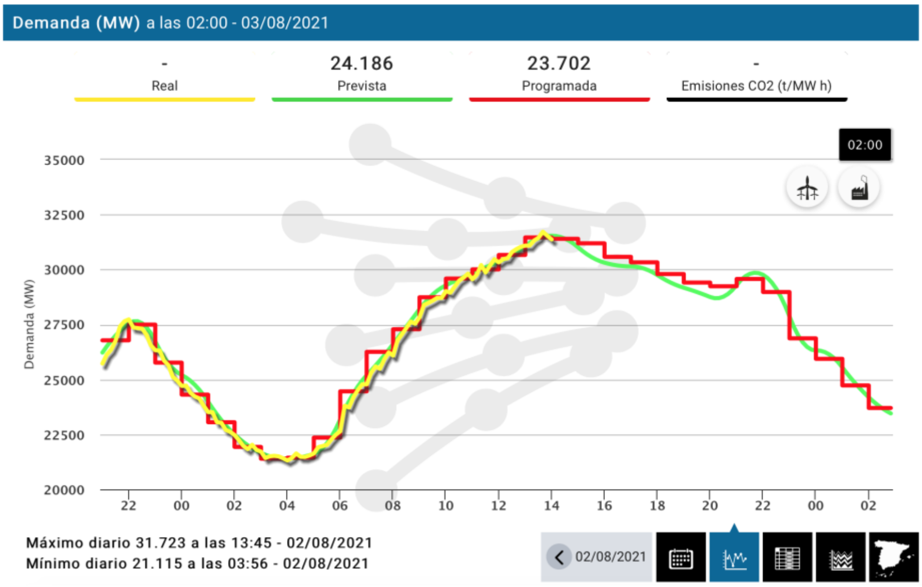

Figure 16. Iberian Peninsula power demand (MW) graph in real time on 03/08/2021. Yellow curve corresponds to real demand. Green and Red curves correspond to preview demand and programmed demand, respectively [5].

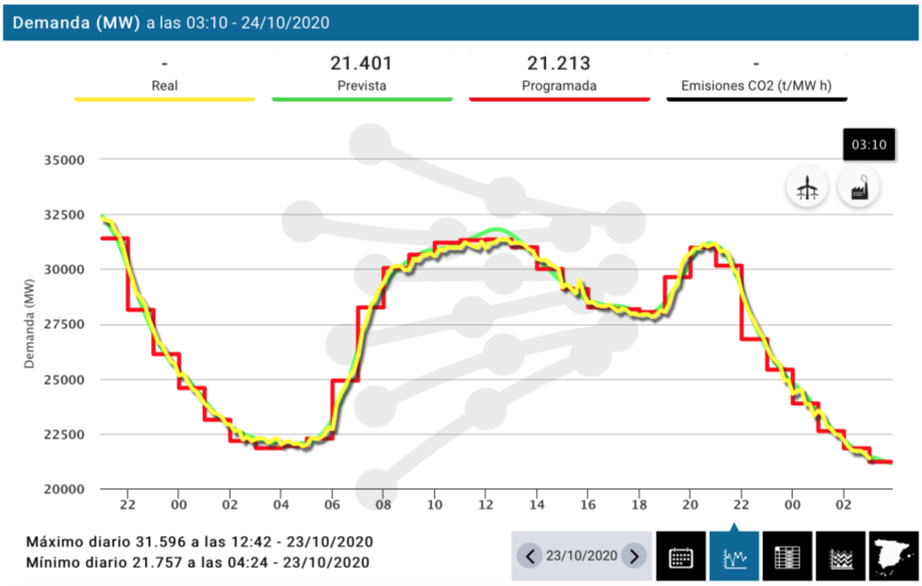

Figure 17. Iberian Peninsula power demand (MW) graph in real time on 23/10/2020. Yellow curve corresponds to real demand. Green and Red curves correspond to preview demand and programmed demand, respectively [5].

As we can see, graphs may vary depending on the month (and day) of the year. Peaks can be detected at around 08:00-14:00h and 19:00-20:00h.

With the daily power consumption data represented in *Table 5* and *Table 6*, the graph shown in *Figure 15* can be extracted.

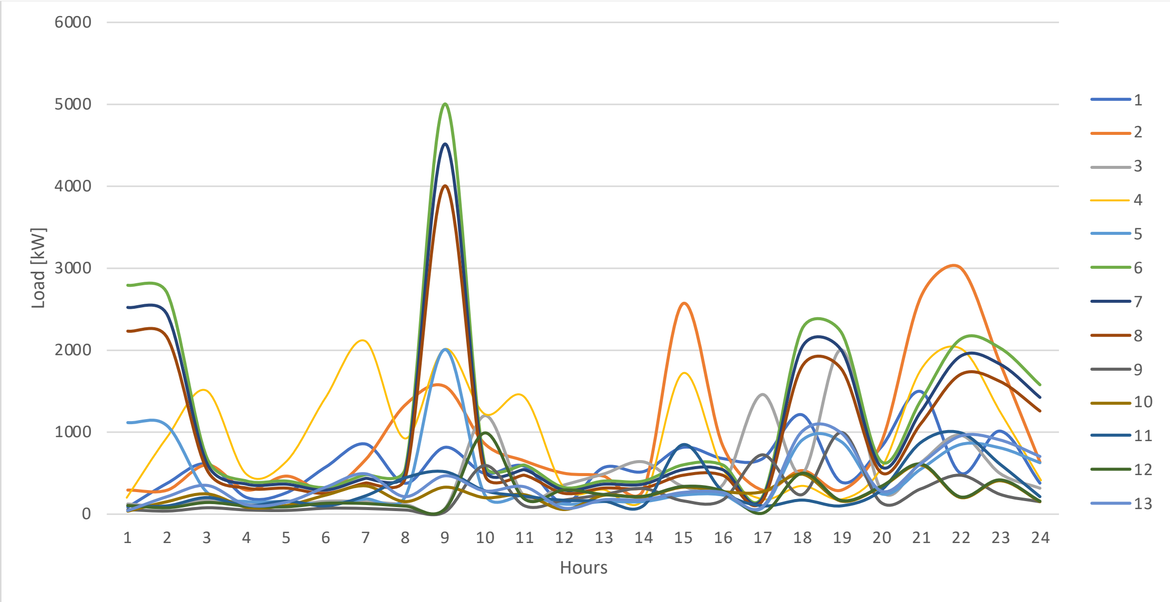

Figure 18. Load (in kW) graph for each prosumer in one day.

In this way, the trend of an entire country in terms of energy demand is not accurately represented, but it does come close by also applying variety among prosumers.

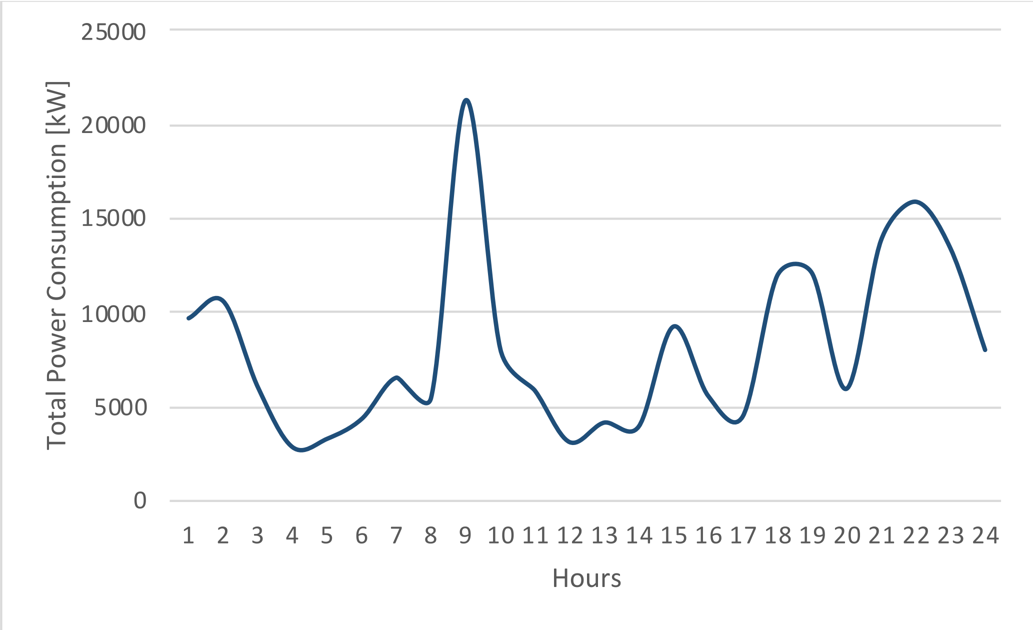

Figure 19. Total load (in kW) graph of the LEC.

The PV production along a day on each prosumer is represented in *Figure 17*. As we can appreciate, the peak values of power generation are given during daylight.

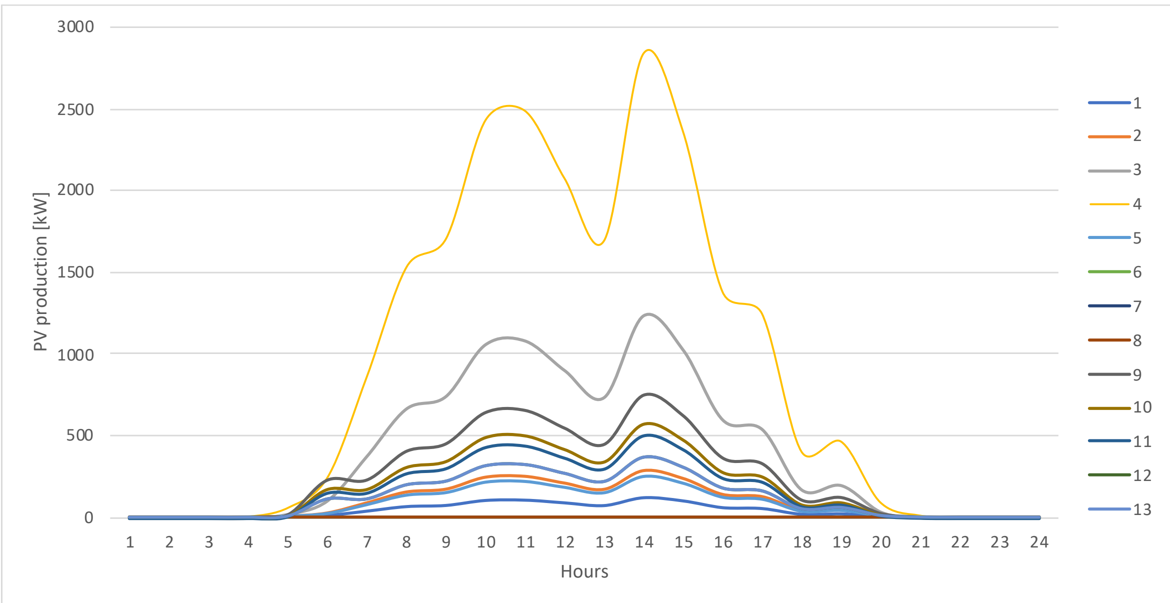

Figure 20. PV production (in kW) graph for each prosumer in one day.

Finally, the assumed prices of buying and selling power to the utility grid are represented in *Table 7* and *Figure 18*. They are also assumed as the energy prices for the exchanges between prosumers for the base case.

Time, t	*Buying price [€/kWh]*	*Selling price [€/kWh]*
1	0,186	0,093
2	0,186	0,093
3	0,186	0,093
4	0,186	0,093
5	0,186	0,093
6	0,186	0,093
7	0,186	0,093
8	0,186	0,093
9	0,336	0,168
10	0,665	0,333
11	0,501	0,250
12	0,336	0,168
13	0,336	0,168
14	0,336	0,168

15	0,336	0,168
16	0,336	0,168
17	0,336	0,168
18	0,336	0,168
19	0,665	0,333
20	0,665	0,333
21	0,542	0,271
22	0,377	0,189
23	0,224	0,112
24	0,186	0,093

Table 7. Buying and selling energy prices with the utility grid.

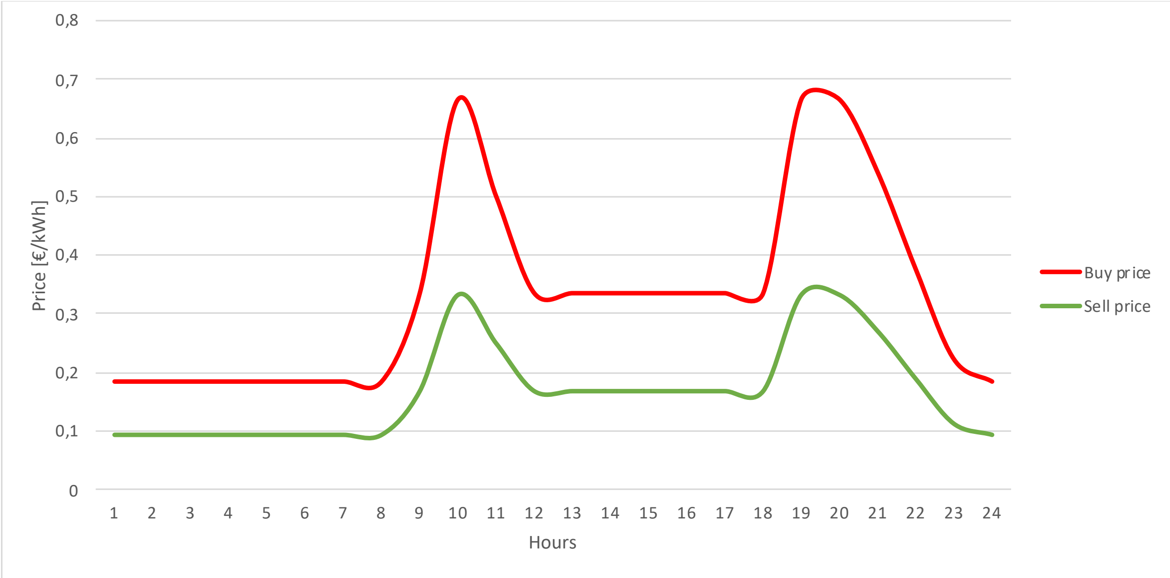

Figure 21. Buying and selling energy prices with the utility grid.

It can be deduced that during peak hours, the price for both buying and selling will be higher. The selling price is assumed lower than the buying price at any instant.

4.3 OBJECTIVE FUNCTION

Given the following sets:

$$Nodes: \ I, \quad with \ i\epsilon\{0, 1, 2, 3, 4, 5, 6, \dots, 11, 12, 13\}$$

$$Branches: \ B, \quad with \ b\epsilon\{1, 2, 3, 4, 5, 6, \dots, 12, 13, 14\}$$

$$Time: \ T, \quad with \ t\epsilon\{1, 2, 3, 4, \dots, 23, 24\}, \quad \Delta t = 1h$$

the following objective function is defined:

$$OF = min \sum_{t\epsilon T, i\, \epsilon I} ((price\_buy(t) * P_{buy\_user}(i,t) - price\_sell(t) * P_{sell\_user}(i,t)) * \Delta t)$$

where $price\_buy(t)$ and $price\_sell(t)$ are the parameters related to the price of the cost/sell operations at each time *t*. The power generated by all prosumers is assumed to be generated by PV panels and thus no costs are related to them. Hence, with this objective function the goal is the minimization of the energy costs of the community. All prosumers are assumed to act in favor of the community.

4.4 RESULTS AND ANALYSIS

The aim of this subchapter is to analyze the results of power consumption and costs of the LEC and compare it to a situation without internal exchanges, in order to justify the implementation of LECs.

Three situations are considered: exchanges between the prosumers and between the different feeders as a LEC, a LEC with separated feeders and a community without internal transactions and separated feeders.

As explained in previous chapters, the constraints force the model to be a Mixed Integer Linear Programming type. The solver used is CPLEX 20.1.0, the most recent version on 2021 of the optimization solver package developed by IBM (International Business Machines Corporation). The platform used for the model execution is AIMMS (Advance Interactive Multidimensional Modeling System) Prescriptive Analytics Platform.

4.4.1. CASE A: BASE DATA

On a first approach, the base data represented in *Chapter 3.2.* is considered.

The Objective Function results for the three different cases are represented in *Table 8.*

CASE A	*OF (Euros)*	*Price difference w.r.t LEC (Euros/day)*
LEC	44.655,62	-
LEC with separated feeders	44.697,22	+ 41,6 ↑
No internal transactions	47.932,53	+ 3.276,91 ↑

Table 8. Comparison of the OF results obtained in AIMMS between different approaches on Case A.

Comparing the OF results given on *Table 8*, it can be deduced that the introduction of a LEC favors the community costs. In this particular case, the difference between a LEC and a community with no internal transactions is a saving of more than three thousand euros per day.

A graph regarding the exchanged power with the utility grid in time domain for the three situations is represented in *Figure 19.*

A graph regarding the total energy of the BES units in time domain for the three different situations is represented in *Figure 20.*

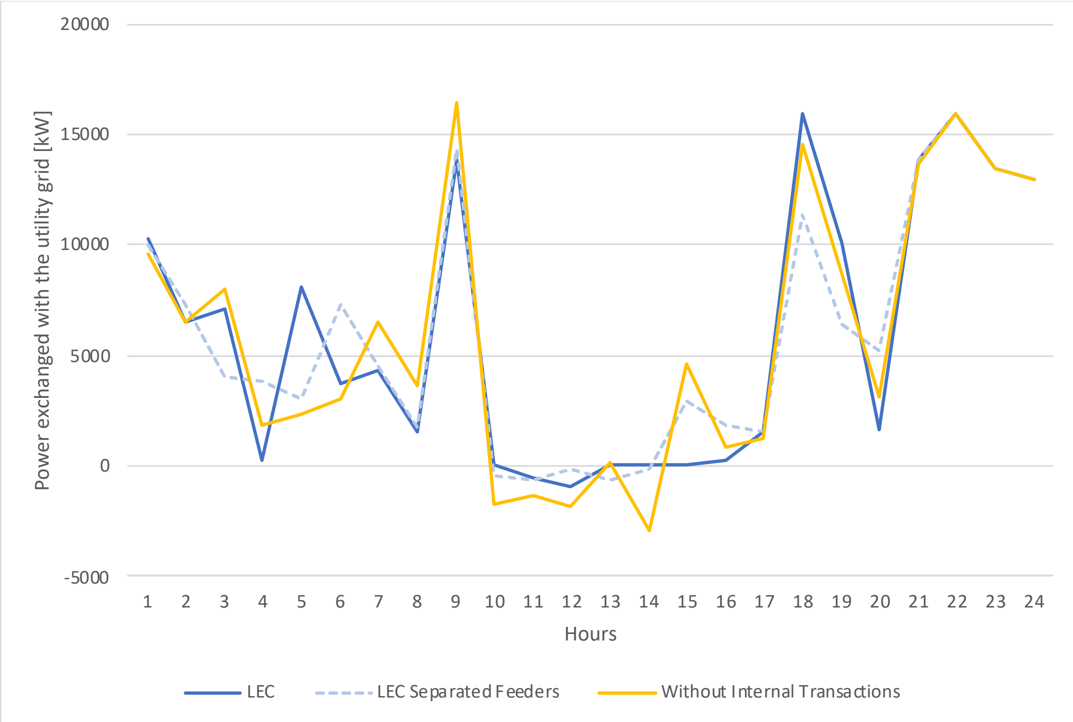

Figure 22. Power exchanged with the utility grid for Case A.

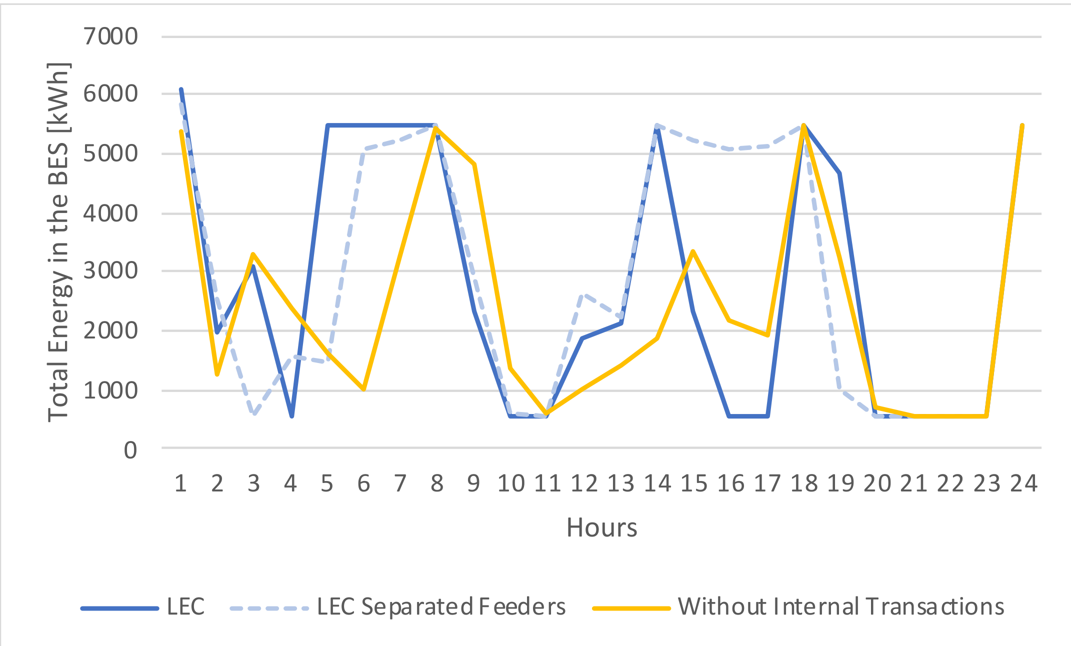

Figure 23. Total energy in the BES units for Case A.

In order to analyze the cost difference between prosumers, *Table 9, Table 10* and *Table 11* are represented below.

Prosumer, i	*Total energy costs per prosumer [Euros]*
1	4.221,54
2	6.530,55
3	1.559,45
4	948,28
5	2.672,75
6	8.817,44
7	8.162,13
8	6.939,04
9	366,08
10	383,78
11	986,03
12	1.101,02
13	1.967,52

Table 9. Total energy costs comparison between users for the LEC (Case A).

Prosumer, i	*Total energy costs per prosumer [Euros]*	*Price difference w.r.t LEC [Euros]*
1	4.305,03	+83,48 ↑
2	6.587,55	+57,00 ↑
3	1.573,99	+14,54 ↑
4	1.031,41	+83,12 ↑
5	2.704,15	+31,39 ↑
6	8.817,23	-0,21 ↓
7	8.207,72	+45,59 ↑
8	6.859,98	-79,04 ↓
9	402,58	+36,50 ↑
10	148,48	-235,29 ↓
11	1.031,62	+45,59 ↑
12	1.080,97	-20,05 ↓
13	1.946,48	-21,04 ↓

Table 10. Total energy costs comparison between users for the LEC with separated feeders (Case A).

Prosumer, i	*Total energy costs per prosumer [Euros]*	*Price difference w.r.t LEC [Euros]*
1	4.463,81	+242,27 ↑
2	6.822,64	+292,09 ↑
3	1.723,64	+164,19 ↑
4	1.290,24	+341,95 ↑
5	3.021,96	+349,20 ↑
6	9.052,33	+234,88 ↑
7	8.394,99	+232,86 ↑
8	7.125,94	+186,90 ↑
9	658,62	+292,54 ↑
10	430,54	+46,77 ↑
11	1.337,43	+351,39 ↑
12	1.305,74	+204,72 ↑
13	2.304,64	+337,12 ↑

Table 11. Total energy costs comparison between users for the community without internal transactions (Case A).

As it can be deduced from the tables mentioned above, the introduction of a LEC reduces not only the global costs of the community but also of each prosumer in particular. It should be noted that, when comparing the LEC situation with the LEC with separated feeders, most of the prosumers save money, but there are some of them that lose money. For instance, prosumer i=10 loses 235,29 euros per day if a LEC is used instead of a LEC with separated feeders.

4.4.2. CASE B: INSTALLATION OF PV PANELS

In this case, PV panels are installed on prosumers 6, 7 and 8, so that they have power generation. The purpose of this measure is to reduce the power costs not only for those prosumers but also for the whole community. For simplicity, the PV production of prosumers 6, 7 and 8 is assumed to be equal to prosumers 1, 2 and 3, respectively.

The OF results for this case are expressed in *Table 12*.

CASE B	*OF (Euros)*	*Price difference w.r.t LEC (Euros/day)*
LEC	41.292,06	-
LEC with separated feeders	41.293,53	+1,47 ↑
No internal transactions	44.071,18	+ 2.779,12 ↑

Table 12. Comparison of the OF results obtained in AIMMS between different approaches on Case B.

As it can be seen, the global costs of the community are reduced in all three situations. Furthermore, as in the previous case, the community with no internal transactions has the biggest amount of global economic cost.

The power exchanged with the utility grid and the total energy in the BES units of the community in time domain are represented in *Figure 21* and *Figure 22*, respectively.

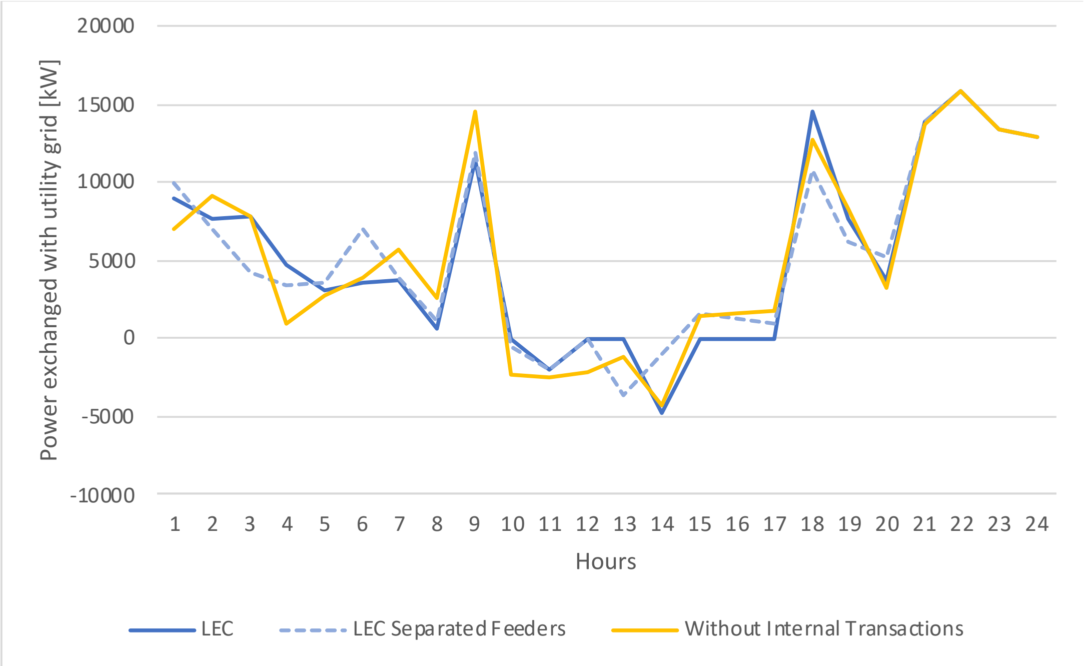

Figure 24. Power exchanged with the utility grid for Case B.

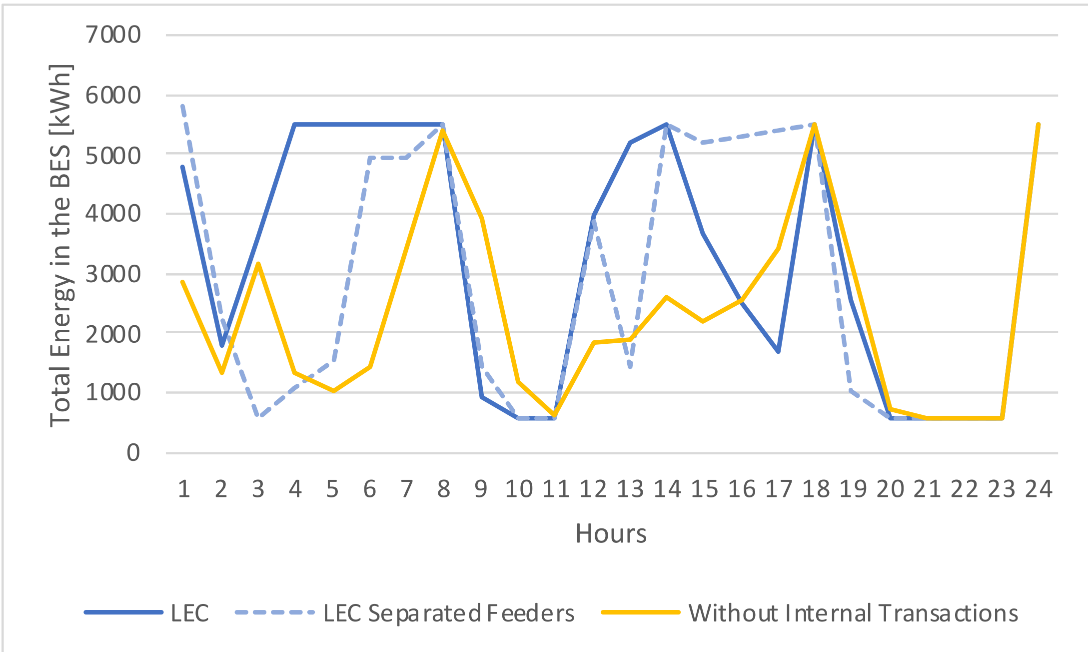

Figure 25. Total energy in the BES units for Case B.

The cost difference between prosumers for the LEC is represented in *Table 13*.

Prosumer, i	*Total energy costs per prosumer [Euros]*	*Price difference w.r.t LEC of Case A [Euros]*
1	4.256,18	+34,64 ↑
2	6.565,19	+34,64 ↑
3	1.575,58	+16,12 ↑
4	1.042,68	+94,39 ↑
5	2.715,02	+42,26 ↑
6	8.784,58	-32,86 ↓
7	7.355,32	-806,81 ↓
8	4.244,18	-2.694,90 ↓
9	380,99	+14,91 ↑
10	365,19	-18,58 ↓
11	1.005,55	+19,52 ↑
12	976,35	-124,66 ↓
13	2.025,28	+57,77 ↑

Table 13. Total energy costs comparison between users for the LEC (Case B).

As it can be seen, the prosumers where the PV panels have been installed (6,7 and 8) have now lower costs. Clearly, the highest savings correspond to prosumer 8, then prosumer 7 and lastly prosumer 6. In order to better understand those differences, *Figure 26* is represented.

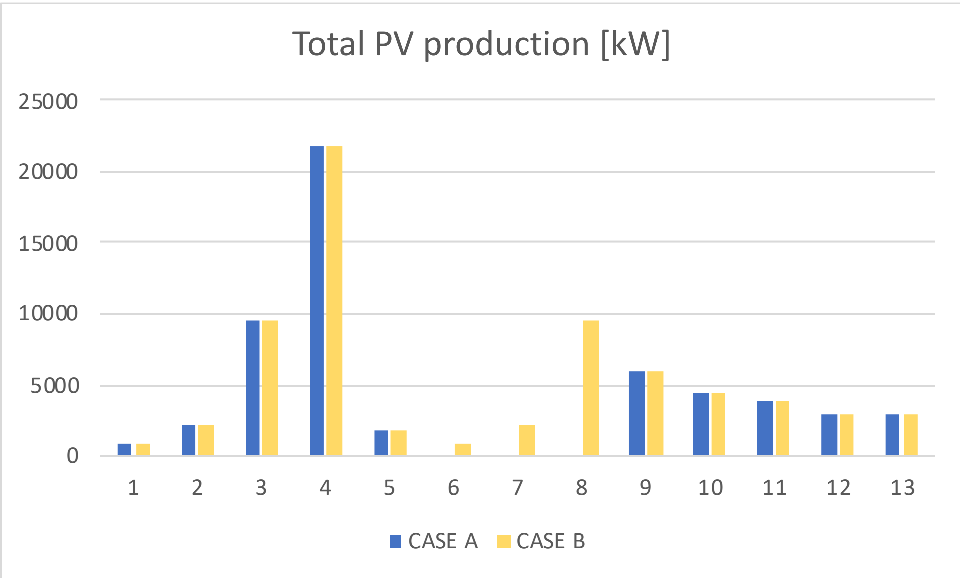

Figure 26. Total PV production comparison between prosumers for both cases.

The higher savings on prosumer 8 are due to the higher PV production of their panels compared to prosumers 6 and 7.

The cost differences between prosumers for the LEC with separated feeders and for the community without internal transactions are represented in *Table 14* and *Table 15*.

Prosumer, i	*Total energy costs per prosumer [Euros]*	*Price difference w.r.t LEC of Case B [Euros]*
1	4.349,21	+93,03 ↑
2	6.631,73	+66,55 ↑

3	1.618,18	+42,60 ↑
4	1.075,59	+32,91 ↑
5	2.757,91	+42,89 ↑
6	8.653,70	-130,87 ↓
7	7.411,79	+56,47 ↑
8	3.979,47	-264,66 ↓
9	413,92	+32,93 ↑
10	214,15	-151,04 ↓
11	1.067,22	+61,67 ↑
12	1.079,09	+102,74 ↑
13	2.041,55	+16,26 ↑

Table 14. Total energy costs comparison between users for the LEC with separated feeders (Case B).

Prosumer, i	*Total energy costs per prosumer [Euros]*	*Price difference w.r.t LEC of Case B [Euros]*
1	4.463,81	+207,62 ↑
2	6.822,64	+257,45 ↑
3	1.723,64	+148,06 ↑

4	1.290,24	+247,55 ↑
5	3.021,96	+306,94 ↑
6	8.705,99	-78,59 ↓
7	7.587,31	+231,99 ↑
8	4.418,61	+174,48 ↑
9	658,62	+277,62 ↑
10	408,44	+43,24 ↑
11	1.342,79	+337,25 ↑
12	1.322,48	+346,12 ↑
13	2.304,64	+279,35 ↑

Table 15. Total energy costs comparison between users for the community without internal transactions (Case B).

4.4.3. GENERAL COMPARISON

Finally, the two cases (Case A and Case B) are compared.

	OF (Euros)	*Price difference w.r.t Case A (Euros/day)*
LEC Case A	44.655,62	-
LEC Case B	41.292,06	-3.363,56 ↓

Table 16. OF results comparison between cases for the LEC.

	OF (Euros)	*Price difference w.r.t Case A (Euros/day)*
LEC with separated feeders Case A	44.697,22	-
LEC with separated feeders Case B	41.293,53	-3.403,69 ↓

Table 17. OF results comparison between cases for the LEC with separated feeders.

	OF (Euros)	*Price difference w.r.t Case A (Euros/day)*
Without internal transactions Case A	47.932,53	-
Without internal transactions Case B	44.071,18	-3.861,35 ↓

Table 18. OF results comparison between cases for the community without internal transactions.

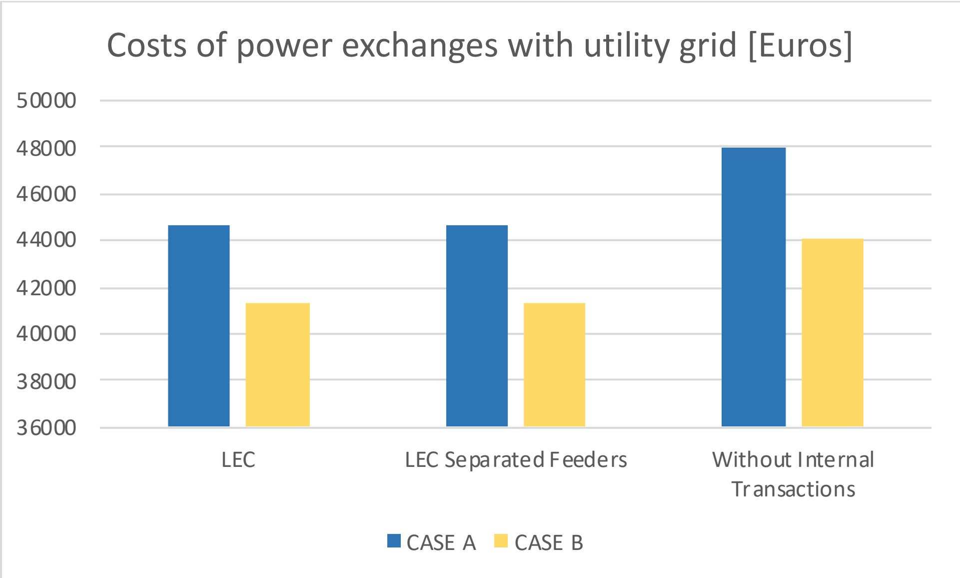

Figure 27. Comparison of the total costs of power exchanges with utility grid for the three situations.

As it can be seen, the Case B where more PV panels are introduced is more profitable than the Case A for any situation. A prosumer experiences a decrease of energy costs when introducing PV generation. Furthermore, the introduction of a LEC is more profitable than a community without internal transactions in terms of global community costs.

5 CONCLUSIONS

In this project, a LEC of thirteen prosumers has been represented in order to minimize the energy costs of the exchanges with the utility grid by programming methods using AIMMS platform. For the sake of simplicity, a DC approximation has been used in order to keep the linearity of the constraints. It allows a first estimation of the flows in the network. A more redefined model is needed in order to appropriately estimate the power losses in the feeders and voltage constraints.

In this project, the profitability of a LEC over other communities without internal transactions has been demonstrated. In addition, the need to quickly introduce renewable energies into the system has been expressed. The economic and environmental benefits make the LEC concept profitable and sustainable. However, an analysis of each community must be carried out in such a way that the benefits of prosumers and the community in general are optimized, so that the conflicts of interest between prosumers are minimal.

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