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MODELLING COOPERATIVE BEHAVIOUR AMONG CONSUMERS IN THE INVESTMENT DECISION-MAKING IN DISTRIBUTED GENERATION

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MODELADO DEL COMPORTAMIENTO COOPERATIVO DE LOS CONSUMIDORES EN LA TOMA DE DECISIONES DE INVERSIÓN EN GENERACIÓN DISTRIBUIDA

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RESUMEN DEL PROYECTO

El impacto medioambiental de la generación de energía ha aumentado la importancia de la integración de las energías renovables en el mix energético. La generación distribuida es una forma relevante de introducción de estas energías limpias, generando cerca de los puntos de consume evitando largas distancias de transporte de la energía. Para acelerar la transición energética hacia un modelo sostenible, se estudian diferentes soluciones. Dentro de esta amplia gama de ideas se incluyen las smart grids, el autoconsume y la gestión de la demanda para hacer este proceso más eficiente incluyendo al autoconsumidor como persona de interés en la cadena de valor de la energía. En este sentido, este trabajo sitúa al consumidor final como parte de la toma de decision en la cadena de valor de la energía, siendo un *prosumer* que puede producer y consumer su propia energía generada. Algunos factores que incentivan la autogeneración y el autoconsume incluyen los precios de electricidad elevados y variables, la dependencia de combustibles externos y la conciencia social sobre el cambio climático.

Por otra parte, la inclusion del consumidor en la inversion de los recursos para producir su propia energía ha de estar acompañada de incentivos que hagan la decisión le compense. Los incentivos que motiven al consumidor pueden ser económicos, medioambientales o incluso un incentivo de autonomía para no depender de los precios y la regulación del Mercado centralizado. Los aspectos económicos tienen en cuenta un riesgo que puede ser también distribuido entre usuarios movidos por los mismos motivos. De esta forma, las comunidades energéticas surgen como un grupo de consumidores que pueden cooperar para obtener beneficios comunes al gestionar la energía conjuntamente. Desde abril de 2019, la regulación española recoge la idea de autoconsume colectivo para

invertir y operar una instalación conjunta en una comunidad energética. Este es el tema abordado en el trabajo aquí realizado.

En el contexto de una comunidad energética, se analizan los posibles beneficios que puede introducir la cooperación. Desde el punto de vista económico, un grupo de consumidores buscan cooperar con la finalidad de reducir su factura de la electricidad.

Con esta finalidad, se comparan en el trabajo dos modelos diferentes:

- Un modelo no cooperativo, donde los agentes operan de forma individual y optimizan sus propios costes.
- Un modelo cooperativo en el que los agentes pueden formar coaliciones para obtener un ahorro respecto a la situación individual, y optimizan los costes de la coalición de forma conjunta.

Se modela el comportamiento cooperativo relacionado con la inversión y operación de la generación distribuida y a continuación se analiza el impacto económico.

El modelo se basa en cuatro viviendas diferentes de una comunidad energética situada en Madrid, España. Para cubrir su demanda de electricidad, estos agentes pueden instalar placas solares o comprar electricidad de la red. En el caso de generar exceso de energía, esta puede venderse a la red o almacenarla en baterías. La optimización se desarrolla en el modelo MACOP, que incluye la formulación matemática de los costes y las restricciones.

Para el modelo no cooperativo, cada vivienda obtiene su decisión de inversión y operación optimizada en el modelo. Por otro lado, para el modelo cooperativo, la decisión de inversión y operación obtenida es conjunta para toda la coalición, cuya demanda es la suma de las demandas de los integrantes de dicha coalición. Por último, se distribuyen los costes obtenidos en este modelo cooperativo entre todas las viviendas integrantes y se comparan con los obtenidos de la optimización individual. Si la vivienda implicada obtiene beneficio al operar conjuntamente, decide quedarse en la coalición.

Para distribuir los costes entre los agentes, se comparan dos métodos diferentes:

- El valor de Shapley (*Sh)*, es un método de repartición de costes de la teoría de juegos cooperativos.
- Una distribución proporcional de los costes entre los miembros de la coalición con un factor de proporción de la energía anual consumida por cada uno de ellos (*Prop)*.

Una vez comparado ambos modelos, si un agente no obtiene beneficio económico porque su coste de la cooperación es mayor que el individual, deja la coalición y se forma una nueva. Cuando todos los agentes obtienen beneficio económico, la coalición es estable y el proceso de simulación se termina.

Los resultados obtenidos muestran que viviendas con perfiles de consumo diferentes pueden obtener beneficios económicos como resultado de la cooperación. La salida de un primer escenario simulado demuestra que se obtienen ahorros en los costes cooperativos respecto a los optimizados de forma individual, en una coalición de todas las viviendas de la comunidad. No obstante, se demuestra también en un segundo escenario, que al cambiar el consumo se puede cambiar de tarifa y por lo tanto la cooperación deja de aportar beneficios. Concretamente, al sobrepasar los 10kW de potencia contratada, los términos de la tarifa regulada son mayores (2.1.A) y por tanto los agentes tienen menores costes actuando de forma independiente, sin sobrepasar el rango de tarifa (2.0.A). En este caso, si algún miembro del grupo decide salir porque no obtiene beneficios, se forma una nueva coalición excluyéndolo, siguiendo la metodología propuesta. De tal forma, se repite el proceso de optimización de costes, y se vuelven a ejecutar ambos modelos cooperativo y no cooperativo, para comparar los resultados de la nueva coalición. Al obtener la coalición estable con todos los miembros ahorrando costes, se termina la ejecución, como sucede en la segunda iteración del escenario 2 simulado.

Esta metodología permite validar si al unirse diferentes consumidores obtienen beneficio económico. Además, los dos métodos de distribución de costes en el método cooperativo dan resultados diferentes en los costes para cada agente. Los resultados muestran que en la asignación de costes con el valor de Shapley se considera la contribución marginal de cada individuo a la coalición a la que se une. Es decir, que la carga económica que el agente individual aporta se tiene en cuenta a la hora de repartir el coste común, perjudicando o beneficiando a cada miembro de forma correspondiente. Por otra parte, al distribuir los costes en función de la energía consumida por cada vivienda, no se contempla el impacto económico marginal, como el efecto del pico de demanda puntual, sino únicamente el total anual. Por lo tanto, el método de distribución de costes de Shapley es más apropiado y justo, beneficiando o perjudicando a cada agente en función de su coste real aportado. No obstante, este método no reparte el coste más bajo para los mismos agentes que el método proporcional, y por tanto puede no ser el preferido por todas las viviendas.

La cooperación entre consumidores que comparten los recursos energéticos en una comunidad energética puede incluir beneficios económicos, respecto a la operación independiente. Además, los cambios en la demanda pueden desestabilizar las coaliciones debido a cambios tarifarios.

La metodología y el modelo propuesto tienen futuro potencial para implementar coaliciones con un número mayor de agentes, con otras comunidades energéticas, e incluso añadir otros recursos como los coches eléctricos. La reducción de costes para el consumidor final se puede analizar distribuyendo los costes de la cooperación con ambos métodos propuestos.

A partir del trabajo realizado, se ha escrito un artículo de investigación para ser publicado y presentado en el congreso *16th International Conference on the European Energy Market 2019.*

MODELLING COOPERATIVE BEHAVIOUR AMONG CONSUMERS IN THE INVESTMENT DECISION-MAKING IN DISTRIBUTED GENERATION

Environmental impact of energy generation has increased the importance of the integration of renewable energy resources in the energy generation mix. Distributed generation is a relevant way of introducing these clean resources, generating the energy close to the points of consumption, avoiding long transport distance of this energy. To accelerate the energy transition towards a cleaner system, different solutions are being approached. In this vast range of ideas smart grids, autoconsumption, load management are included as possible development axes. These solutions often involve the end consumer in the energy management to make the whole process more efficient adding this stakeholder. In this sense, this thesis sets the end energy consumer as part of the decision-making in the energy chain being a prosumer that can produce and consume its generated electricity. Some factors motivating self-production and consumption involving consumers in the energy generation chain, include the high and fluctuating electricity prices, the dependence on external fuel and the awareness on climate change.

Moreover, the engagement of end user on the investment of resources to produce its own energy must come with incentives that make the decision worth it. This can be incentivised by economic benefits, by environmental facts to “go green” or even by autonomy incentive to not depend from the wholesale market prices or regulation. Economic aspect includes a risk that can be distributed or shared with nearby users moved by the same motives. In this way, energy communities emerge as a group of people that can cooperate to obtain common benefits by their jointly energy management. From April 2019, the Spanish regulation introduces the concept of collective autoconsumption with the idea of jointly invest and operate common installation in an energy community. This is the addressed issue in the work performed.

In the context of an energy community, the possible benefits of cooperating are analysed. From the economic point of view, a group of consumers would aim to cooperate in order to reduce their energy bill.

For this purpose, two models are compared:

- A non-cooperative model, where households operate individually and optimise their individual costs.
- A cooperative model where households may form coalitions to obtain savings respect to the stand-alone operation and optimise jointly the coalition's costs.

The cooperative behaviour related to the distributed generation investment and operation is modelled and the economic impact is analysed.

The model is based on four different households of a energy community located in Madrid, Spain. To cover their energy consumption, these households may install photovoltaic panels or buy electricity from the grid. If there is any excess of energy, it may also be sold to the grid or stored in batteries. The optimisation is performed in the MACOP model, which includes the mathematical formulation of all involved costs and constraints.

For the non-cooperative model each household would obtain its according optimised investment and operation decision. For the cooperative model, a unique agent is assumed with a load equal to the addition of loads of all members that cooperate. A common decision for investment and operation is here obtained. Finally, the costs are allocated to each member, and compared to the individual ones obtained in the non-cooperative model. If the household involved obtains benefits from the cooperation, it would opt to stay within the coalition.

The allocation of costs is performed and compared by two different methods:

- The Shapley value (*Sh),* which is a method to allocate costs of cooperative game theory based on the concept of fairness.
- A proportional distribution of the total cost depending on each households' annual energy demand, (*Prop).*

If a household does not obtain economic benefit and its allocated cost is greater than its stand-alone cost, it would leave the coalition, and a new one would be formed. Once all households obtain economic profit, the coalition would be stable and simulation procedure would be stopped.

Results obtained show that households with different consumption profiles can obtain economic benefit when cooperating. The output of a first scenario proves that economic benefit is obtained from a grand coalition formed by all households with different loads.

However, it is also proven in this work, that if load profile changes, and tariff terms vary, as shown in a second scenario, the cooperation may not be any longer profitable. If any household within the group would opt to exit it because its savings are not positive, a new coalition is then tested without him in another iteration, repeating the procedure of cost optimisation. Finally, when all members within the coalition obtain savings respect to the stand-alone operation, the coalition would be stable.

The two distribution methods used to allocate the cost of the cooperative model, give different results for each household, depending on their load profile. Results show, that the allocated cost according to the Shapley value considers the marginal contribution of the household to the coalition that it joins. On the other hand, the proportional distribution depending on the annual energy consumed, does not include the effect of peak demand on the cost when it enters a coalition. This means that the Shapley value would be more appropriate in the sense of fairness awarding or punishing each household depending on the cost it includes. However, this cost sharing method, may not allocate highest savings to the same households as other methods, and therefore may not be preferred by all members.

Overall, cooperation among prosumers that share energy resources in a residential energy community can lead to economic profit, more beneficial than individualistic operation. Moreover, changes in the demand of the community can destabilize the coalition due to changes in the energy regulated tariff range. The proposed methodology and model have further potential to implement larger coalitions and involve other resources such as electric vehicles in the energy community. The reduction of costs for end users can be analysed allocating shared costs by both proposed methods.

From the work performed, a research paper has been written to be published and presented in the 16th International Conference on the European Energy Market 2019.

Index

Figures

Tables

Chapter 1 INTRODUCTION

The proposal of the Directive of the European Parliament and of the council on common rules for the internal market in electricity [1], states that 50% of renewables sources of energy could reduce the greenhouse gas emissions in the European Union by at least 40% until 2030. The share of the electricity produced from these renewable sources will continue to increase and it is a key element to fulfil the European Union's obligations described in the Paris Agreement on climate change. This proposal also points out how the renewable energy sources will play an increasing role in the generation mix and that the end consumers should be able to participate in the energy markets. The Directive of the European Parliament also sets the consumers in the front line of the energy transition making them active participant in the coming energy markets. It is also announced in this same document how regulations should be updated to set common rules for prosumers, users that consume, produce, store and share the energy with other users, [1]. Appropriate legal frameworks are demanded in this proposal in order to introduce local energy communities that can generate and consume with or without a connection to the distribution system. In Article 2 of the proposal, local energy community is defined as follows: "local energy community means: an association, a cooperative, a partnership, a non-profit organisation or other legal entity which is effectively controlled by local shareholders or members, generally value rather than profit-driven, involved in distributed generation and in performing activities of a distribution system operator, supplier or aggregator at local level, including across borders".

Apart from this European proposal, the fluctuations of energy prices, the dependency on external fuels to produce electricity, and the social awareness on climate change are other factors driving the integration of distributed energy resources into the grid through these energy communities, based on renewable sources. The energy communities add generation value in the Energy value chain, adapting different solutions for the distributed energy generation, from self-production and self-consumption to the introduction of peer-to-peer trading platforms to exchange the surplus of energy in local markets instead of the traditional wholesale market [1].

1.1 MOTIVATION

The cost of electricity is a concern for end-users and, as domestic distributed generation is expected to increase due to its possible impact in the reduction of these costs, the study of this topic is very relevant. As renewable distributed generation opens a wide range of possibilities to reduce the cost of energy of the end-users, the cooperation between consumers is identified as a key idea to investigate and test this economic benefit. In addition to the growth of renewables and distributed resources in the grid, the decrease of solar photovoltaic and batteries' costs facilitates the installation of panels in residential levels. As neighbour countries such as Germany and United Kingdom have already installed around 1.600.000 and 800.000 residential solar panels respectively for autoconsumption, Spain that benefits from more than the double of solar radiation is a relevant target to implement this operation [2]. Moreover, the change in the Spanish regulation is encouraging the expansion of residential solar installations, that according to a study of the *Observatorio Español del Autoconsumo Fotovoltaico* more than 300.000 residential homes will have solar autoconsumption installations in the next three years[2]. Collective autoconsumption is also introduced in the Spanish regulation in April 2019, where a signed agreement on how to distribute the common installation costs is required to assess the cooperation [3] before the energy community is formed.

This thesis analyses if the cooperation between households makes sense and if it can reduce the final individual costs with respect to individualistic behaviours. The potential benefits of the coalition are identified, and a model is developed to evaluate these potential benefits. More specifically, the cooperation between households in the installation of photovoltaic panels and batteries for autoconsumption is analysed and numerically assessed for some case examples. It is assumed that the users can produce part of their own electricity and sell the surplus to the grid or store it and can also purchase power from the grid produced by the utilities, in case it is needed.

1.2 OBJECTIVES

The decrease of installation costs of photovoltaic panels as well as battery storage systems', and the relevant role of the prosumers' communities, that until now have not had, in the energy transition, is combined in this thesis in the pursuit of the minimisation of the users' energy costs. In the scenario of the possible cost reduction for the prosumers due to their cooperation, the main objective of this thesis is to analyse the economic impact, for a residential coalition among households, of the installation and operation of photovoltaic solar panels generation and energy storage. The comparison between cooperative and non-cooperative prosumers in the investments and energy management decisions lead to economic results where conclusions are obtained.

Moreover, the aim of this thesis is to assess the benefits of cooperation in the investment decision of distributed renewable generation for an energy community in Spain, compared to the absence of cooperation, when installing photovoltaic solar panels and lithium batteries. To achieve this target, the following partial objectives are addressed:

1. Mathematical formulation of the energy bill of a community of prosumers that have the possibility to invest in distributed generation considering individual bill minimization, or a cooperative approach (modelled with cooperative game theory). The minimization of the energy bill is implemented in a GAMS prototype.
2. Design of test scenarios to validate the resulting model.
3. Economic assessment of the benefits of cooperation. Using the developed model, applied to the grid selected in the precedent objective, the economic assessment of a cooperative behaviour versus the individual bill minimization is performed under different scenarios.
4. Study of the feasibility of applying the model developed in a larger generation expansion model for a better modelling of the distributed generation expansion.

1.3 METHODOLOGY

The objective function to minimise is the cost of energy of a community and the optimisation tool used is GAMS. The tasks carried out include:

1. Review of the state of the art.

   The previous work related to cooperative operation in the energy sector are reviewed. Mainly, work related to energy communities and shared resources in residential distributed generation. Cooperative game theory is introduced to use distribution methods applied to allocate common costs in the energy community. It is studied how other works use these methods for fair distributions of common benefits over a group of agents.
2. Identify the parameters needed for the developed model.

   The residential energy community is modelled in ad for which electricity prices and tariffs in Spain are applied. The resources used are PV panels and lithium batteries. Finally, the energy community includes four households with different load profiles to supply from the main grid or from the installed resources.
3. Formulate the total costs of the households' energy bill, including the investment of the PV panel and battery, the energy self-generated, energy self-consumed, energy bought from the grid and surplus sold to the grid.
4. Formulate the total costs under a collaborative scheme, using cooperative game theory for costs sharing among the participants, and comparison with the costs of individualistic approaches.
5. Develop the optimisation model in GAMS.

   The differences between the cooperative and non-cooperative model are identified to simulate a procedure and analyse the economic output of the model. The individual operation of households is firstly simulated in gams, followed by the simulation of the coalition. Finally, both models' outputs are compared by analysing the cost per agent.

6. Design simulation scenarios to validate the model and test.

   The demand is varied to identify the impact on the results of the coalition and the variation in the corresponding energy costs. Different tariff ranges are applied to the coalition to compare results. For each scenario with different input, the algorithm applied follows:

   - Simulation in GAMS for non-cooperative and cooperative model
   - Calculation of costs for each agent. The result of the cooperative model is distributed using 1) the Shapley value of cooperative game theory and 2) a demand proportional allocation of costs that depends on the energy consumed by each household.
   - A coalition where all households obtain benefits is searched, being this a stable coalition. If no agent reduces its costs by cooperating, the new coalition is recalculated in order to acquire stability.

7. Results analysis, conclusions, and final report writing.

   Results of cooperation issues as well as differences between costs allocation methods are withdrawn.

1.4 RESOURCES

The study of the existing cooperative models and collective solutions to manage the energy at a residential level is the result of the analysis of the existing literature.

The model has been programmed in GAMS using the license of the IIT. The input parameters are imported from Excel where the CEVESA input tool of the IIT has been used, programmed in VBA. The output values have also been exported to Excel for their further analysis using a tool that is able to load and compare GDXs files that result from GAMS executions.

Chapter 2 STATE OF THE ART

As mentioned, the objective of this thesis is to assess how different the economic results can be when neighbours cooperate in the distributed energy sources investment and management compared to individualistic approaches.

In this regard, article [4] includes an exhaustive study to gather the recent relevant research that has been done related to the prosumer community groups, that generate and share energy, and the prosumer's relationship. This relationship between producer and consumer is explained in this article, where in the reciprocal relationship both parties benefit from working together. It is here concluded that a group of consumers that sell energy to the grid is more efficient and reliable in the sense of providing sustainable energy supply than an individual prosumer on its own., as they obtain bargaining power and can reduce energy loss. Another highlighted conclusion is that the effective relationship between prosumers enable successful smart grids when having a common goal, they'd benefit from working together. This paper finally proposes future works such as testing real-life scenarios to have more realistic results to understand why prosumers join a community or act on its own.

Reference [5] states that the energy communities enable a group of individuals to gather and develop partnerships in order to secure investments and reduce risks. According to the same reference, the union between households is used to increase the initial capital and build an installation that would have been out of reach for individuals. Furthermore, the collaboration in the energy communities that generate their energy can introduce additional profits for each consumer, and this is studied in the article. This cooperative system is an additional way to accelerate the energy transition whose target is to maximize the share of renewables in the energy mix. Moreover, the decrease of the PV panel prices makes this source of energy the focus of the energy communities which can lead the future of energy.

Apart from [4] and [5] that provide a literature review of the benefits of cooperating in the energy sector, other more specific papers use game theory to mathematically represent cooperative behaviours. The application of game theory has been extensively described reaching a very wide range of disciplines from medicine to economics and politics. Game theory can be divided into non-cooperative and cooperative game theory. Non-cooperative game theory has been mainly used in the analysis of the decision-making process of independent players within a competitive market. Some of the benefits introduced by the cooperation among users that have been studied using game theory are:

- Monetary benefits, due to avoided penalties of shortages in production [6], or due to different pricing between micro-grids than in the wholesale market [7].
- Reduction of power losses [8]–[11].
- Fair allocation of network costs [12].
- Fair allocation of investment costs [13], [14].

Monetary benefits

Collaboration between distributed energy resources (DER) in energy markets is studied in [6]. They formulate the allocation of the profit between the distributed generators using different methods, including the Shapley Value, which is one of the main methods to share the benefit between players in cooperative games. A bi-level structure is proposed: a primary level where each generator maximizes its generation applying non-cooperative game theory and a secondary level where the profit is allocated between the members applying cooperative game-theory. Each coalition includes resources with excess of power to sell, also energy districts that require power to supply their consumers. Before joining the game, each player evaluates its possible benefit using the Shapley Value. In this same reference, the individual profit of each DER is calculated with a numerical example using the Shapley value, the nucleolus algorithm or the merge and split algorithm and all of them compared to the calculation without coalition. The results show that the profit obtained due to the cooperation is higher than the one obtained from individual performance. The profit of the DERs in this example is increased in the coalition due to the excess of production that enables them to exchange energy avoiding access tariffs by not selling to the grid and due to the avoided penalties of shortages in production.

Reduction of power losses

The **power losses** in the distribution lines are the main focus of [8]–[11]. In these articles, the coalition introduces a benefit to the system because the distance between microgrids can be reduced with respect to the distance between the micro-grid and the grid.

In [8] a model to formulate the exchange of energy between smart grids is developed. A Smart grid is a power network that includes intelligent nodes in order to communicate and interact with each other, with the aim of efficiently deliver electricity to the users [15]. The thesis [8] does not consider exchange with the global grid, and the objective function is to minimize the power losses in the distribution grid by considering different coalitions between smart grids. The results show that coalition between specific smart grids reduce the power losses due to lower distances and the resulting distribution of power flows.

The coalition between micro-grids with surplus of power to sell and microgrids that need to acquire power to fulfil their demand is the same approach of [10]. The objective function here is the power loss costs of each micro-grid. The division of pay-offs is not done using fairness methods of cooperative game theory but using proportional division considering the weights of each micro-grid. The results of the simulation implemented show a reduction up to 31% of power losses in the distribution line compared to a non-cooperative case.

To form the coalitions, in [11], the distance between the microgrids is the main parameter they consider in the model. The conclusion in this case is that the more coalitions are formed, the highest reduction of power losses is obtained, due to the reduction of transmission distance, since no local generation was previously installed.

The potential of the energy exchange between nearby micro-grids is also featured in [9]. According to this article, the cooperation can reduce the waste of power during the energy transmission in the distribution lines, and a local exchange reduces the reliance and the demand from the main electric grid. Unlike before mentioned articles, a mathematical formulation is not here included. However, other applications of game theory to the electrical sector like demand-side management and communications are mentioned.

Fair allocation of network costs

Cooperative game theory is also a convenient tool to solve **cost allocation** problems [16], as it has been done in [12]. It is here described a fair allocation of costs of the transmission network in the electricity market. The Shapley value is also used in this article to share the revenues of a grand coalition among smart grids. Moreover, cooperative game theory introduces distribution methods such as the Shapley value or nucleolus, in order to allocate the total value of a coalition among its members based on the concept of fairness.

Fair allocation of investment costs

As part of the distributed generation, energy communities produce their energy close to the point of consumption. An energy community is an aggregation of households of a common building or of a close geographical area that jointly produce their energy and have a common source of costs [13] also defined by the European Community in Introduction. The coalition between households within an energy community to install and produce renewable energy, can be motivated by financial incentives to reduce the economic and political power (energy autonomy), or by ecological incentives to go green, contributing to decarbonization targets[17]. In [13] it is described how self-consumed electricity can allow the users reduce their network charges and how using cooperative games, a collective can distribute the costs of installation of solar panels, according to their consumption. The allocation of costs among residential users with photovoltaic panels on rooftops can be analysed with cooperative game methods such as the nucleolus and the Shapley value as it is done in [14]. In these two articles, the benefits of the cooperation are the costs sharing methodology of a commonly used product, and using game theory, enabling to allocate correctly the costs of this product to use it. In [18] the revenue obtained from the cost saved collaborating in comparison to the individual performance is distributed by means of the Shapley Value. In this work, the financial benefits obtained from the collaborative method come from the exchange of energy at different prices between prosumers in the energy community, as users can obtain lower costs selling energy between them than the access tariff and electricity price of the grid.

Other areas of study of residential energy efficiency

Making the end user a central agent for an efficient energy transition does not only incur in the management of the distributed renewable generation but also in the demand management. Other papers like [19], [20], focus on the energy management from the demand point of view, for example scheduling the power to reduce the peak demand of residential users.

Other current applications of cooperative game theory in the energy sector have been plug-in electric vehicles and storage systems. These systems will not be considered in this thesis, but the way to integrated them in the developed model will be addressed based on the formulation proposed in [21].

Overall, the field of application of game theory to the formation of coalitions among users in the energy sector is very extensive. The different advantages obtained by different approaches to cooperation make this modus operandi appealing and is the focus of this thesis.

Chapter 3 RESIDENTIAL DISTRIBUTED GENERATION INVESTMENT MODEL

3.1 MODEL DESCRIPTION

A residential energy community formed by prosumers is modelled. The operation and investment in energy sources such as battery and photovoltaic panels is analysed. Households within the energy community may operate and/or invest individually or in cooperation with other households of this community. To evaluate the economic impact of cooperation, two different models are formulated:

1. Non-cooperative model: each household of the energy community invests and operates its energy independently, minimizing its energy costs.
2. Cooperative model: households in the energy community form coalitions and optimise their operation and investments jointly to minimise total energy costs.

For the evaluation of the non-cooperative model, each household can invest in photovoltaic panels to generate electricity and in lithium batteries to store it. They can also buy and sell energy to the main grid. In order to efficiently operate the energy and to optimise the investment decisions, a minimisation of costs is formulated. Each household has an independent load profile and a connection to the grid.

The energy to cover the load of each household can be supplied from three sources:

- the grid, from where it is bought
- batteries, where it was previously stored
- photovoltaic panels where it is generated

Each household can also sell energy to the distribution grid or store it in the battery for later use.

The following diagram represents the energy flow for each agent in the energy community:

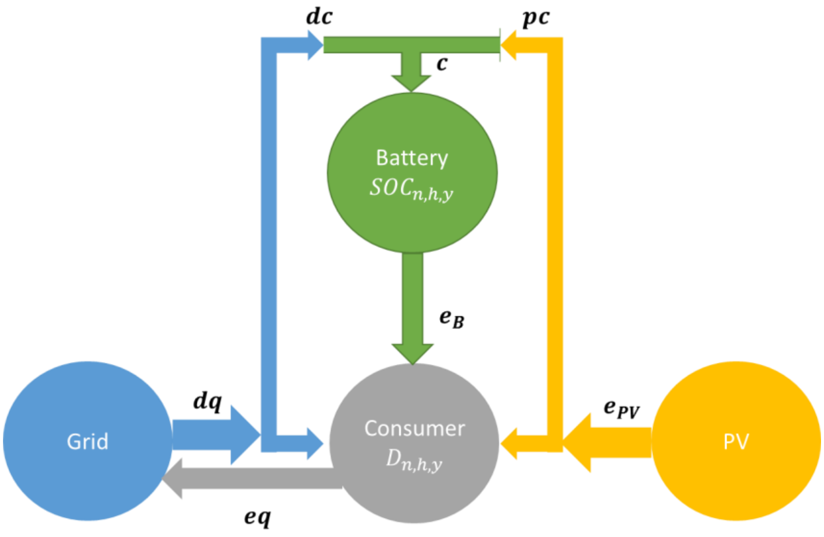

Figure 1 Energy flow of a household

For the evaluation of the cooperative model, there is a unique connection to the main grid as well as a common PV installation that distributes to all households of the coalition. In addition, there is a common battery acquired by the community. The energy flow is analogous to the non-cooperative model, as the load of the community can be supplied from the battery, the grid or the photovoltaic panels. However, the investment and the operation are jointly optimised to obtain the minimum costs for the energy community. Therefore, the cooperation is modelled as a unique agent with the addition of loads, covered by common resources.

To understand the real effect of cooperation, the same users with and without cooperation are studied with the same type of resources, under the same tariffs first and with different tariff range changed by an increase in the total demand after, in order to identify the changes in costs. In this way changes in the investment decision and in the final costs due to cooperation can be identified.

3.2 ASSUMPTIONS

Common assumptions for cooperative and non-cooperative models

- The energy community modelled is located in the south of Madrid, Spain, where the Spanish regulation of 2018 is applied, regarding grid tariffs.
- No batteries nor PV panels are installed before the simulation of the model.
- Investment of technologies are paid the first year of the simulation of the model.
- Operation and maintenance costs of batteries and PV panels are neglected.
- Same tariff is applied to the net energy exchange with the grid.

Assumptions for non-cooperative model

- Each household invests and operates its own resources (batteries and panels)
- Same product type of battery and photovoltaic panels are assumed for all agents. Size and capacity to install of these resources vary depending on the optimisation for each household.
- Each household maximizes its cost function independently.
- Excess of energy is sold to the grid after the meter of each household, therefore the Access tariff is paid by each user individually.

Assumptions for cooperative model

- The coalition invests and operates the energy resources jointly
- The demand of the coalition is calculated as the sum of all hourly members' profiles.
- There is only one connection point to the grid, where the energy from the grid enters and where the excess is injected into the grid

3.3 NON-COOPERATIVE VS COOPERATIVE MODEL: SIMILARITIES AND DIFFERENCES

The two models have similarities and differences, as listed in the following table:

	Non-cooperative Model	Cooperative Model
Similarities	Same resources: Li-ion batteries, PV panels Same constraints: load balance, PV constraints, battery constraints	
Differences	Objective function: individual minimization of costs The cost of each household is obtained from the optimisation Several connection points to the grid	Objective function: total minimization of costs The cost of each household is obtained by an allocation method One connection point to the grid

Table 1 Similarities and differences between models

Therefore, in the non-cooperative model, each household minimises its own objective function. In the cooperative model, the objective function is unique and results in the total costs of the cooperation, being the coalition represented as a unique agent optimising its costs.

3.4 MATHEMATICAL FORMULATION

In this section the mathematical formulation for the problem that minimizes the investment and operation costs of individual households or cooperating agents is presented. For both models, cooperative and non-cooperative, the nomenclature and constraints are equal, however, in the non-cooperative model, the index n denotes each household whereas in the cooperative model n represents the whole coalition. This coalition S (being $2^N$the number of possible coalitions) is represented as one fictious household. The obtained results of the coalition will be then distributed among the members of it.

3.4.1 NOMENCLATURE

Index/ sets		*Units*
t	Technology: PV system or Battery energy storage system: PV, B	-
n	Household, $n \in \{1,2,\dots,N\}$	-
h	Time period in 1-hour increment, $h \in \{1,2,\dots,H\}$	-
w	Weeks, $w \in \{1,2,\dots,W\}$	-
y	Year, $y \in \{1,2,\dots,Y\}$	-
Parameters		
$D_{n,h,y}$	Load profile	kWh
TP_y	Fixed part of the grid tariff for contracted power	€/kW
TE_y	Variable part of the grid tariff for the energy consumed	€/kWh
TC_y	Variable part of the grid tariff for the energy sold	€/kWh
$\lambda_{h,y}$	Electricity price	€/kWh
$IC_{t,n,y}$	Investment cost of each technology	€
$FU_{n,h,y}$	Utilisation factor of PV panel	%
FC_y	Battery energy-to-power ratio	Wh/W
ηd_n	Discharging efficiency of battery	%
ηc_n	Charging efficiency of battery	%
$WI_{h,w}$	=1 if $h$is the first hour of the week w and =0 otherwise [0,1]	-
$WF_{h,w}$	=1 if $h$is the last hour of the week w and =0 otherwise [0,1]	-
Variables		
$dq_{n,h,y}$	Energy bought from the grid	kWh
$c_{n,h,y}$	Energy charging the battery	kWh
$dc_{n,h,y}$	Energy charging the battery from the grid	kWh
$pc_{n,h,y}$	Energy charging the battery from PV	kWh
$eq_{n,h,y}$	Energy injected to the grid	kWh
$e_{t,n,h,y}$	Energy generated from each technology	kWh
$p_{t,n,y}$	Installed capacity of each technology	kW
$dp_{n,y}$	Contracted power	kW
$ip_{t,n,y}$	Increase in the installed capacity	kW
$soc_{n,y}^{max}$	Maximum state of charge of the battery	kWh
$soc_{n,h,y}$	State of charge of the battery	kWh

3.4.2 OBJECTIVE FUNCTION

The objective function is the sum of terms that determine the annual cost of energy C_n.

The cost function is the addition of:

- Costs due to the grid connection
  - fixed term related to the installed capacity: $TP_y \cdot dp_{n,y}$.
  - variable term related to the energy consumed $\left(\lambda_{h,y} + TE_y\right) \cdot dq_{n,h,y}$ and the energy injected into the grid $eq_{n,h,y} \cdot \left(\lambda_{h,y} - TC_y\right)$.
- Investment costs due to the installed capacity of the PV panels and batteries. The aging costs of the battery as well as the operation and maintenance costs varying with the energy consumed from these technologies are here neglected.

$$\begin{gathered} C_n = \\ \sum_y TP_y \cdot dp_{n,y} \\ + \sum_{h,y}\left[\left(\lambda_{h,y} + TE_y\right) \cdot dq_{n,h,y} - eq_{n,h,y} \cdot \left(\lambda_{h,y} - TC_y\right)\right] \\ + \sum_{t,y} IC_{t,n,y} \cdot ip_{t,n,y} \quad \forall\, n \end{gathered} \tag{1}$$

In the model where households do not cooperate, each agent minimises its objective function depending on its own consumption profile and installed technologies. As households are mutually independent, their optimization is solved at the same time by including all constraint in a unique mathematical programming problem that minimizes the summation over $n\ of C_n$.

In the cooperative model, there is a pre-process, where the demand is calculated as the sum of the load profiles of all households within the coalition.

$$D_{h,y} = \sum_n D_{n,h,y} \tag{2}$$

3.4.3 CONSTRAINTS

LOAD BALANCE

The demand of each household or coalition, at each time slot, is supplied by the energy bought from the grid and by the installed technologies. In case there is an excess of energy, it is sold to the grid or charged into the battery to store it.

$$dq_{n,h,y} + \sum_{t} e_{t,n,h,y} = D_{n,h,y} + eq_{n,h,y} + c_{n,h,y} \tag{3}$$

CONTRACTED POWER

The contracted power (dp) must be higher that the energy bought from the grid (dq) and injected into the grid:

$$dp_{n,y} \geq dq_{n,h,y} \tag{4}$$

$$dp_{n,y} \geq eq_{n,h,y} \tag{5}$$

INSTALLED CAPACITY

The total installed capacity (p) of each technology includes the investment at the beginning of the year (ip) and is bounded by a maximum threshold (P^{max}):

$$p_{t,n,y} = p_{t,n,y-1} + ip_{t,n,y} \leq P_{t,n,y}^{max} \tag{6}$$

The maximum installed capacity of a coalition is calculated as the sum of the corresponding bounds for all households. The installed capacity is therefore obtained with the number of PV panels and batteries(n) with a capacity (P):

$$p_{t,n,y} = n_{t,n,y} \cdot P_{t,n} \tag{7}$$

PHOTOVOLTAIC PANEL

PV utilisation factor is dependent on the solar radiation and emplacement, varying the energy produced by the panels(e):

$$e_{PV,n,h,y} = FU_{n,h,y} \cdot p_{PV,n,y} \tag{8}$$

The energy generated by the panels(e) can be also used to charge the battery:

$$e_{PV,n,h,y} \geq pc_{n,h,y} \tag{9}$$

BATTERIES

The state of charge of the battery(soc) is calculated with the state of charge of the previous hour, the energy discharged from the battery (e)and the energy charge in the battery(c), modelling the battery energy balance:

$$soc_{n,h,y} = soc_{n,h-1,y} - \frac{e_{B,n,h,y}}{\eta d_n} + c_{n,h,y} \cdot \eta c_n \tag{10}$$

Maximum State of Charge is limited by the lithium-ion battery specifications:

$$soc_{n,y}^{max} = FC_y \cdot p_{B,n,y} \tag{11}$$

$$soc_{n,h,y} \leq soc_{n,y}^{max} \tag{12}$$

The battery is charged from the grid (dc) and from the PV panels (pc):

$$c_{n,h,y} = dc_{n,h,y} + pc_{n,h,y} \tag{13}$$

The energy bought from the grid (dq) is used to supply the demand and to charge the battery:

$$dq_{n,h,y} \geq dc_{n,h,y} \tag{14}$$

Finally, it is assumed that the battery has weekly cycles and the state of charge of the batteries at the end of each week are the same as at the beginning of the week:

$$\sum_{h,y} WI_{h,w} \cdot soc_{n,h,y} = \sum_{h,y} WF_{h,w} \cdot soc_{n,h,y} \tag{15}$$

Chapter 4 METHODOLOGY

This chapter presents the proposed methodology to compare cooperative and non-cooperative behaviours in the energy community. Game theory is firstly introduced, as it is one of the used methods to share the benefits of cooperation. Following, costs allocation methods are explained, and the procedures implemented for the simulation are shown.

4.1 INTRODUCTION TO GAME THEORY

Game theory was firstly introduced and described in 1944 in *Theory of Games and Economic Behaviour* [22]. A game is a situation where decisions are to be made by players with a strategic interdependency, governed by a set of rules and a defined result. Game theory differentiates between two types of games. In non-cooperative or competitive games each player searches to maximize its own benefit without interacting with other players in the game, choosing its best strategy to decide. On the other hand, in cooperative games, players may agree before the game and cooperate forming coalitions of players with the aim of maximising the total benefit. The main issue related to cooperative games is that, once the maximum benefit is obtained, it must be shared among the participants of the coalition. The main objective of cooperative game theory is to analyse the impact of each player in the collection of that benefit, to propose an adequate repartition of it among the players [23]. As introduced in the State of the art, several studies have applied the concept of Shapley value to the allocation of costs in the energy sector, more specifically between agents within an energy community.

Cooperative Game Theory

Cooperative game theory consists on the coalition formation of several players to obtain a common benefit or saving [23]. A coalition can be formed by any number of players, and the benefits of the coalition are shared between the players. The game is defined by a finite number of players: $N = \{1,2, \dots, n\}$ that can form up to 2^n possible coalitions [14], and a characteristic function that represents the worth or the payoff of the coalition.

Each coalition is represented by $S \subseteq N$, and its corresponding worth is represented by $v(S)$. The grand coalition is the set of all players N. The characteristic function associated to each subset S of N is a real number and it is the payoff, being $v(\emptyset) = 0$.

Fair allocation of costs

The distribution of the value of the coalition $v(S)$ is denoted by x and it is a vector of payoffs where x_i is the payoff obtained by player i. This vector verifies the group rationality and individual rationality properties which means that the total payoff is divided among all players in the coalition and that a player will join the coalition only if it obtains more benefit than operating individually[14]:

$$\sum_{i \in N} x_i = v(N) \tag{16}$$

$$x_i \geq v(\{i\}) \; \forall i \in N \tag{17}$$

The coalition is stable, meaning that all members obtain benefit and therefore opt to be part of this coalition, if there is no other coalition that can provide a higher payoff for any of the players. Even if the grand coalition offers the lowest costs for the players, the coalition is only stable if all obtain the highest payoffs of all possible coalitions.

The Shapley Value is a solution concept of cooperative game theory proposed in 1953 that provides a fair allocation of costs as all participants are compensated proportionally to their marginal contribution to the total cost. This method assigns a unique value to each player, based on four axioms[14].

1. Efficiency: the total payoff of the coalition is the sum of the individual payoffs; therefore, the value of the coalition is completely allocated. $\sum_{i \in N} \varphi_{i_i} = v(N)$.
2. Symmetry: players that contribute equally to the coalition receive the same payoff, so players i and j are symmetric if $v(S \cup i) = v(S \cup j)$, for any coalition $S \subseteq N$.
3. Null player: if the contribution of a player is zero, its allocated payoff is also zero. Null player i:$v(S) = v(S \cup i)$.
4. Additivity: the sum of two independent games u and v is the sum of the value of each game:$\varphi(u + v) = \varphi(u) + \varphi(v)$.

For a given game(N, v), the only solution that satisfies these four properties is the Shapley Value, used in this work as one of the distribution methods.

4.2 COST ALLOCATION

The result of the optimised objective function in the cooperative model is the solution for a group of households and provides the costs to be allocated among them. The distribution methods used to allocate the costs of the cooperative model in this thesis are the Shapley Value, beforementioned, as a method of fairness, and the method based on the energy consumed by each household. Both methods are explained, and their results compared.

4.2.1 SHAPLEY VALUE

This solution assigns to each player in the energy community $n \in N$ a real number $\varphi_n(C,S)$ of the total cost of the coalition $C(S)$, depending on its marginal contribution $C(S) - C(S\{n\})$.The marginal contributions of each player are averaged over all possible different combinations of coalitions in the game:

$$\varphi_n(C,S) = \sum_{S\prime \in P(S)} \frac{C(R(S')\cup\{n\}) - C\big(R(S')\big)}{|S|!} \tag{18}$$

where P(S) are all the possible permutations of coalitions S, and $R(S')$ is the set of households preceding n in the permutation S'. Since the total cost of each coalition $C(S)$does not depend on the order of the households in S, then the term $C(R(S')\cup\{n\}) - C\big(R(S')\big)$is repeated in the summation of (17). The number of times this term is repeated coincides with $|S'|! \cdot (|S| - |S'| - 1)!$. Therefore, the Shapley value is calculated as:

$$\varphi_n(C,S) = \sum_{S'' \subseteq S\{n\}} \frac{|S'|! \cdot (|S| - |S'| - 1)!}{|S|!} \cdot \big(C(S''\cup\{n\}) - C(S'')\big) \tag{19}$$

The cost added by player n when joining coalition S' is $C(S''\cup\{n\}) - C(S'')$, which is the marginal contribution to the coalition. This term is multiplied by the $|S'|!$ different ways the coalition S' could have been formed prior to agent n's addition. Then, it is multiplied by $(|S| - |S'| - 1)!$ different ways the remaining agents could be added after. Finally, it is averaged dividing by $|S|!$ number of all possible coalition combinations.

Moreover, the value added by each participant is its marginal contribution and it is the increase of cost obtained when the household joins the group. The Shapley value provides the fair allocation as all players are compensated proportionally to their contribution[24]. Player n is incentivised to stay in the coalition S if its stand-alone cost C_n is higher than its cost obtained from the cooperation $\varphi_n(C, S)$.

4.2.2 PROPORTIONAL ALLOCATION OF COSTS

As exposed in [13], basic distribution rules such as pro-rata of consumption or peak demand do not always provide an adequate remuneration for all players cooperating and therefore the coalition may not be stable as some players would opt out of the community if their cost is lower in an stand-alone procedure than in the collaborative form. However, this method will be evaluated and compared to more complex and elaborated sharing rule explained before, the Shapley value.

As the total cost, explained in 3.4.2, is calculated based on the supplied demand, following this different method, the energy costs of the coalition will be distributed among the households depending on their consumption profile. Therefore, a percentage factor is calculated based on the annual energy demand of each household.

$$\mu_n = \frac{\sum_{h,y} D_{n,h,y}}{\sum_{n,h,y} D_{n,h,y}} \tag{20}$$

The cost allocated to each household is:

$$\gamma_n = \mu_n \cdot C(S) \tag{21}$$

Where $C(S)$ is the total cost of the coalition obtained from the optimisation problem and is the sum of all allocated costs of the households within the coalition.

Understanding different sharing rules to allocate costs can benefit households and define the more efficient way for them to distribute the costs, so they can have better savings. Moreover, the coalition is already profitable if costs are reduced respect to non-cooperation, but the cost payed by each agent is then needed to be calculated.

4.3 PROPOSED METHODOLOGY TO COMPARE COOPERATIVE VS NON-COOPERATIVE BEHAVIOURS

The explained mathematical model of the energy community is included in GAMS and both the non-cooperative and cooperative models are solved. To compare both, and obtain a stable solution with the optimal set of coalitions C^*, where households obtain economic benefits, the following proposed methodology is applied:

1. Simulate non-cooperative model. Individual energy costs of each household are calculated obtaining C_n.
2. Simulate cooperative model. The grand coalition is assumed, and the total costs of the energy community are calculated $C(S)$. The coalition is formed by all households, $S = N$, $k = 0$ and the current set of optimal coalitions is $C_k = \{S\}$.
3. Costs are distributed between households: $\varphi_n\ (C, S) and\ \mu_n$ for all $n \in S$
   a. According to the Shapley Value $\varphi_n(C, S)$
   b. According to a proportional allocation of costs μ_n
4. Individual costs of the non-cooperative model are compared to the allocated costs of the cooperation model. If $C_n > \varphi_n(C, S)$ is obtained for all households, the coalition is stable, and the simulation ends. All players obtain benefit from cooperating with the energy community, it is an optimal set of coalitions $C^* = C_k$.
5. If a household exists such as $C_n < \varphi_n \rightarrow$ player n leaves the coalition. Start at step 2 with the new coalition excluding player n, C_{k+1}. If every posible C_{k+1}has been tested, then C^*does not exists.

Chapter 5 SCENARIOS AND RESULTS

5.1 INPUT DATA

Input data used for the simulated scenarios are described in this chapter. The two scenarios are performed over a sole year, 2018, in an energy community located in Madrid, Spain, composed of four households.

5.1.1 LOAD PROFILES

The base load profile is calculated based on the average energy consumption of residential agents in Spain included in [25]. Seasonality and labour have an impact on the consumption profile. To consider these effects, a factor is applied depending on the hour of the day, day of the week, the month of the year and the season. The average consumption per day of a household in summer in Spain is 5500W and in winter 9500W [25]. This value is considered the season average consumption (SAC) per day. Applying the hourly consumption variation, following average consumption profile is obtained for winter and summer, where hourly and season effects are shown:

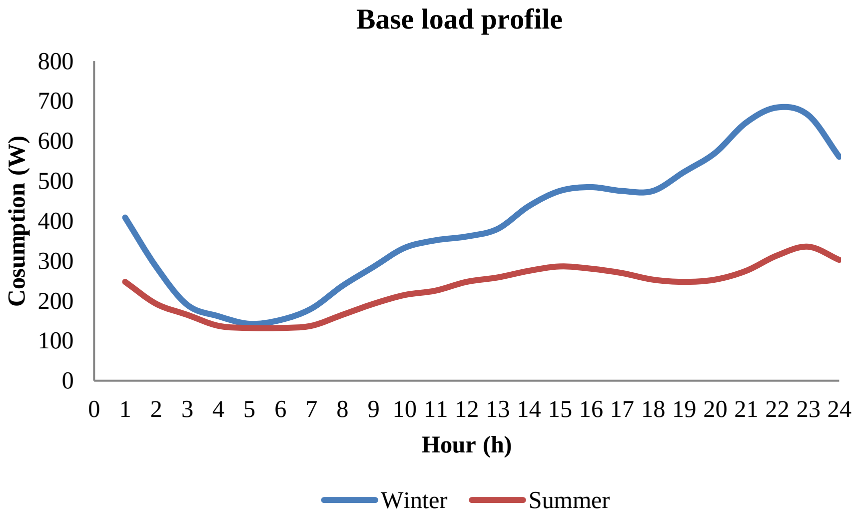

Figure 2 Average load profile in winter and summer

The peaks of consumption are encountered at the latest hours in the evening, representing the 7,20% of the daily consumption at 22:00pm in winter and the 6,10% of the daily consumption in summer. The daily factor of the base load due to labor during the week is represented in Figure 3.

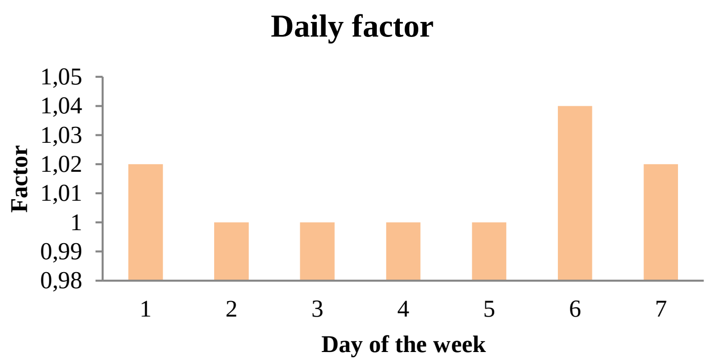

Figure 3 Daily factor of the load profile

The variation of the electricity demand along the months of the year is encountered in a monthly factor shown in Figure 4.

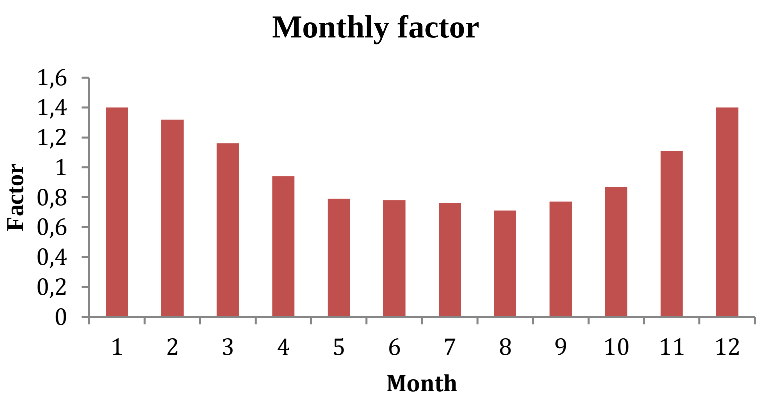

Figure 4 Monthly factor of the load profile

Finally, the increase in energy consumption in Spain per year has been considered.

Year	Energy consumption (GWh)	Annual factor
1996	154245	1
2018	253495	1,6434

Table 2 Residential energy consumption in Spain [25]

Altogether, the base load is calculated applying the correction factors to the average load:

$$D_{n,h,y} = SAC(W) * hour\ factor * day\ factor * month\ factor * year\ factor$$

The energy community studied considers four different households with different load profiles.

Household 1 (H1)	Base load = $D_{1,h,y}$
Household 2 (H2)	No consumption in winter In summer: $D_{2,h,y} = 0{,}8 * D_{1,h,y}$ (months [5-9])
Household 3 (H3)	During the week days: $D_{3,h,y} = 1{,}5 \cdot D_{1,h,y}$ Weekends: no consumption
Household 4 (H4)	Half of base load's consumption $D_{4,h,y} = 0{,}5 \cdot D_{1,h,y}$

Table 3 Assumptions for load profiles 4 households

The resulting monthly load profiles are plotted in Figure 5 and its relevant values are gathered in the following table:

	H1	H2	H3	H4
Annual consumption (kWh)	9951,83	1716,87	7317,04	4975,91
Average consumption (kW)	1,14	0,20	0,84	0,57
Peak consumption (kW)	1,64	0,36	1,65	0,82

Table 4 Relevant data of load profiles

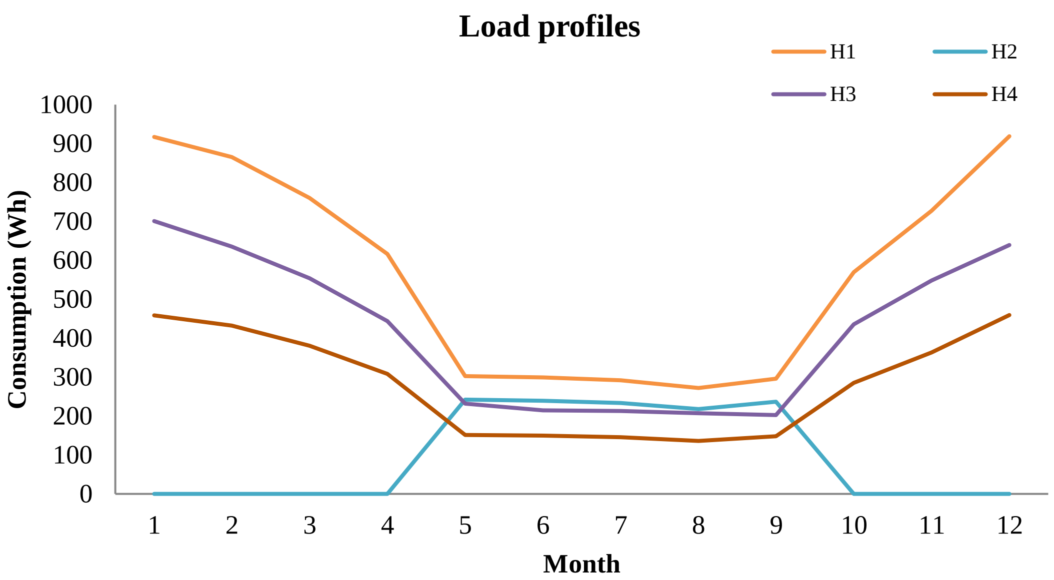

Figure 5 Average load profiles

5.1.2 GRID TARIFF

The grid tariff applied is the regulated tariff in Spain in 2018, obtained from [26].

Tariff 2.0A, P < 10kW		
TP (€/kW)	TE (€/kWh)	TC (€/kWh)
38,043426	0,044027	0,044027
Tariff 2.1A, 10kW<P < 15kW		
TP (€/kW)	TE (€/kWh)	TC (€/kWh)
44,444710	0,05736	0,05736

Table 5 Grid tariff in Spain 2018

TP represents the fixed part of the regulated tariff, affecting the contracted power. The TE and TC are variable terms affecting the energy consumed from the grid. Depending on the annual contracted power, tariff 2.0A or tariff 2.1.A is applied.

5.1.3 ELECTRICITY PRICE

The electricity price varies each hour. The historical data has been obtained from REE [27] for 2018.

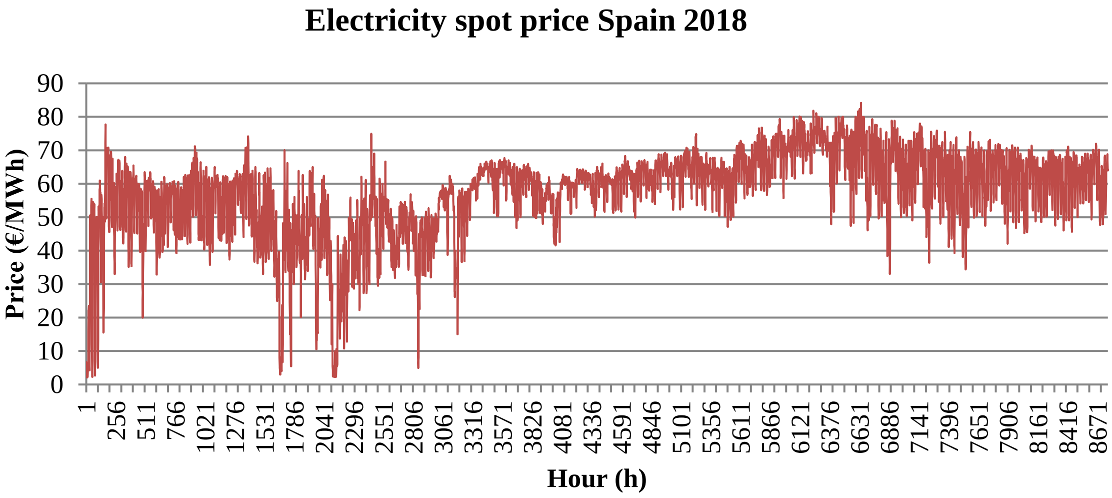

Figure 6 Hourly electricity spot price in Spain 2018

5.1.4 PV AND BATTERY PARAMETERS

1.4 Technologies specifications

Same battery and PV panels are assumed for all households. The investment costs of the battery and the PV panels are obtained from a LAZARD study where three types of batteries are studied with different applications in the electrical grid [28]. For the modelled energy community, lithium-ion batteries have been chosen, for a "Residential PV+Storage" application. Following parameters of the technologies are included in the study for the year 2018:

Efficiency of Storage (%)	86
Battery FC (MWh/MW)	4
Battery life cycle (years)	10
Battery Capital Costs ($/kW)	4826

PV life cycle (years)	20
PV Capital Costs($/kW)	3115,5

Table 6 Technical specifications for PV and battery systems

An exchange rate of *1USD=0,893652 €* is applied to investment costs of the technologies.

2.4 Maximum installed capacity

For the PV panels, the installed capacity is limited by the space available of the energy community. Assuming a space of 50m^2, for PV panels of 0.6m^2 producing 100W each:

$$50m^2 \rightarrow 8{,}3\ kW \ \ maximum\ of\ 83\ panels$$

The number of batteries per household is limited to 2. Each battery has a capacity of storage of 1.1 kW [29].

3.4 PV Utilisation factor

The energy produced by each PV panel depends on the solar radiation calculated according to the emplacement of the installation. The energy community modelled is located in Madrid, where the irradiance is obtained depending on the hour of the day and the month of the year:

$$FU_{n,h,y} = hour\ factor * month\ factor$$

This factor, FU, is multiplied by the production capacity of the PV panels, obtaining the real production capacity of the solar resources. As the emplacement is the same for all households in the community, same utilisation factor is assumed for all households.

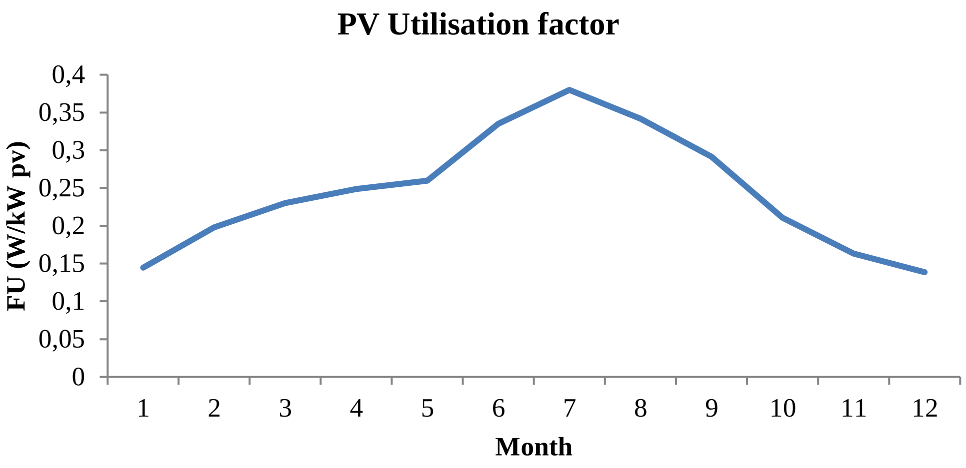

Figure 7 PV production

5.2 SIMULATION SCENARIOS

Two different scenarios are simulated to study the cooperation between agents and stability of coalitions formed. The different inputs between tested scenarios are the load demand and the tariff applied:

	Load profiles	**Tariff terms**
Scenario 1	Load curves described in 5.1.1	Tariff 2.0. A
Scenario 2	Increased load of household 3	Tariff 2.0.A or tariff 2.1.A (depending on the coalition)

Table 7 Simulated scenarios

Firstly, the results obtained for each scenario are shown and then in
Result analysis these costs are broken down and explained.

5.2.1 SCENARIO 1

In the first scenario the grand coalition is assumed, and all four households cooperate, being the first step of the algorithm. Input data introduced in 5.1 are used and the simulation procedure is followed. Firstly, for the non-cooperative model, the four households minimise their costs individually, and different investment and operation costs are obtained for each agent. The connection to the grid is independent for each household, and the input tariff 2.0.A is applied as no contracted power outrages 10kW, after validated as shown in Table 9. The costs of the individual optimisation for each household are shown in Table 8.

Household	**Cost: C_n (€)**
H1	528
H2	105
H3	425
H4	264
Total	*1322*

Table 8 Non-cooperative costs scenario 1

Following step 2 of the simulation procedure, the cooperative model is calculated. For the grand coalition, {1,2,3,4}, a single connection point to the grid is assumed.

As the total peak demand does not exceed 10kW, tariff 2.0.A is also assumed for the cooperative model, and then validated with the results shown in Table 9. The same tariff has been therefore applied to the cooperative and non-cooperative models. The resulting contracted power and installed PV capacity of the simulation of non-cooperative model, for each household (H), and cooperative model are here shown:

		Contracted power dp (kW)	Tariff	Installed PV capacity (kW)
Cooperative model		4,06	2.0.A	1,7
Non-cooperative model	H1	1,64	2.0.A	0,6
	H2	0,36	2.0.A	0
	H3	1,65	2.0.A	0,4
	H4	0,82	2.0.A	0,3

Table 9 Results contracted power scenario 1

The result of this simulation shows that the cost of the energy community when cooperating is lower than the sum of the individual costs previously obtained:

$$C(S) = 1266€ < \sum_{n} C_n = 1322€$$

Therefore, the total cost of the community is lower when cooperating. This is due to the sole connection point to the grid that reduces the tariff term in the total costs, as shown in the breakdown of costs in Table 16 General savings breakdown, where savings from grid costs sum up to 19%. The energy consumed from the PV panels is greater than from the grid in the cooperative model, where investment in PV are greater, than in stand-alone operation. This also affects to the reduced costs from the grid term as less energy is bought to supply the demand when cooperating than in stand-alone operation as shown in Figure 8, where the generation and consumption profile for a winter day, 1st of June 2018, is plotted. In this figure it is also visible that in both models, the maximum production with the PV panel is during the highest hours of irradiation at 13:00pm. For this day plotted the energy sold to the grid is null for both models and the total load remains the same for the whole community, in both models.

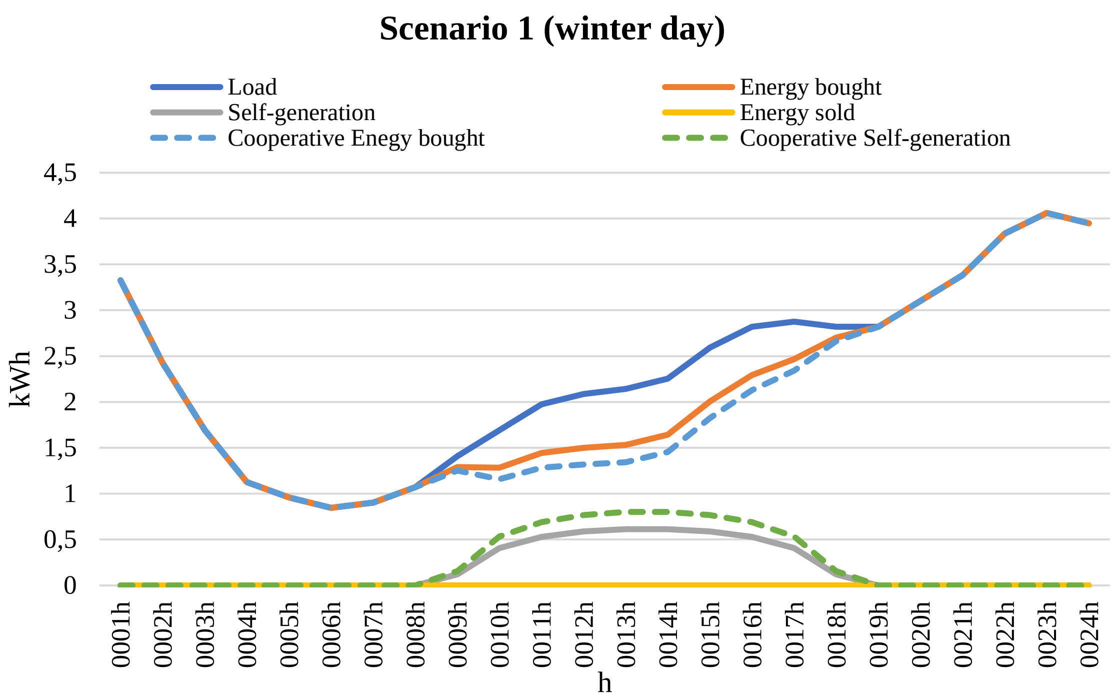

Figure 8 Generation and consumption profiles Scenario 1, winter day

Looking at a different profile, during a summer day, 1st of July 2018, the PV generation is even higher when solar production is more efficient due to solar radiance. Moreover, the load is much lower in summer so even if generation is higher also the energy sold is increased. Again, cooperative scenario self-generates more than stand-alone model.

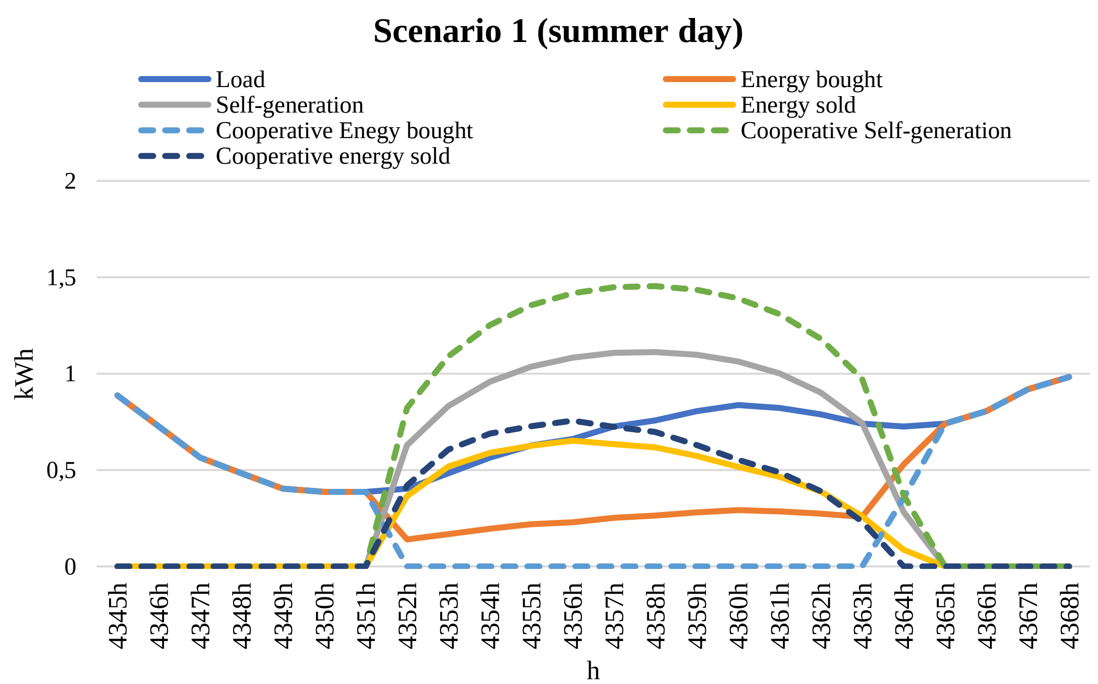

Figure 9 Generation and consumption profiles Scenario 1, summer day

To see if each household is also obtaining benefits from the coalition, therefore to check if the coalition is stable, the total cost is distributed among the households. To do so, according to step 3 of the procedure, the Shapley value $\varphi_n(C,S)(Sh)$ is obtained as well as the distribution according to the energy demand of each agent γ_n (*Prop*).

	Non-coop. model costs (€)	**Cooperative model costs (€)**		**Savings**			
	C_n	***Prop*** γ_n	***Sh*** $\varphi_n(C,S)$	***Prop*** $C_n - \gamma_n$	**Stay in coalition?**	***Sh*** $C_n - \varphi_n(C,S)$	**Stay in coalition?**
H1	528	526	519	0.5%	YES	1,7%	YES
H2	105	91	75	13.6%	YES	28,2%	YES
H3	425	387	413	8.9%	YES	2,7%	YES
H4	264	263	258	0.5%	YES	2,3%	YES

Table 10 Results of costs scenario 1

The results gathered in Table 10 show the individual costs when no cooperation is applied, then the distributed costs when cooperating allocated with two different methods and finally the savings obtained from the cooperative model with respect to the stand-alone operation. Finally, the stability of the coalition is measured regarding the savings obtained from the proportional allocation method and from the Shapley value. If the savings from cooperating respect to non-cooperative method are positive, household would opt to stay in the coalition. In this scenario, savings show a stable coalition according to both methods of allocation of costs, and all households obtain economic benefits from the share of resources and operation. The relative differences required to know if each household stays or leaves the coalition, are all positive, therefore all households would agree to cooperate with the energy community that indeed reduces their annual energy bill.

In addition, comparing the two allocation methods of distribution of costs, household 3 is the only agent obtaining less benefit from the allocation of costs by the Shapley value than from the proportional allocated costs. This is due to its peak demand of its load profile, as further explained in Individual costs of results analysis. Other three households benefit from greater savings with Shapley value cost distribution. Nevertheless, both methods distribute the total costs resulting in a positive profit for all agents respect to the non-cooperative model and therefore the coalition is stable, and the simulation procedure ends with the optimised coalition and costs.

5.2.2 SCENARIO 2

In a second scenario, the load profile of household 3 is increased to analyse the effect of the demand on the cooperation results. The same simulation procedure is applied.

The grand coalition is assumed, formed by all households {1,2,3,4} in iteration k=0. Same input data described in 5.1 is introduced in the model, however the load profile of household 3 is increased up to five times its original value. In this case, the tariff applied to the non-cooperative model is maintained in 2.0.A as no peak demand outrages 10kW, however, in the cooperative model the tariff applied is 2.1.A, and verified in the obtained results exposed in Table 11, with a contracted power of the coalition greater than 10 kW.

		Contracted power dp(kW)	Tariff	Installed PV capacity (kW)
Cooperative model		10,8 kW	2.1.A	3,3
Non-cooperative model	H1	1,64 kW	2.0.A	0,6
	H2	0,36 kW	2.0.A	0
	H3	8,26 kW	2.0.A	2
	H4	0,82 kW	2.0.A	0,3

Table 11 Results of contracted power scenario 2, k=0

The contracted power of the coalition sets the tariff in a higher range increasing the grid cost terms. On the other hand, individuals do not surpass the tariff operating on their own with their sole contracted power. Therefore, the cooperative cost obtained with this data is now greater than the sum of individual costs of agents when they don’t cooperate:

$$C(S) = 3302€ > \sum_{n} C_n = 3020€$$

The costs are higher for the coalition even though the contracted power by the group is less than the sum of the power contracted by individual households (10,8<11,1kW), due to the increase in tariff terms defined in Table 5.

Not only the cooperation implies greater costs due to a change in the range of tariff but also the individual allocated costs are higher for all households than when they operate by themselves, as shown in the following table where it is also visible if, according to each distribution method, the household would stay in the coalition.

	Non-coop. Model costs (€)	**Cooperative Model costs (€)**		**Savings**			
	C_n	***Prop*** γ_n	***Sh*** $\varphi_n(C,S)$	***Prop*** $C_n - \gamma_n$	**Stay in coalition?**	***Sh*** $C_n - \varphi_n(C,S)$	**Stay in coalition?**
H1	528	617	580	-16,9%	NO	-9,8%	NO
H2	105	106	110	-1,4%	NO	-5,0%	NO
H3	2123	2269	2307	-6,9%	NO	-8,7%	NO
H4	264	309	305	-16,9%	NO	-15,3%	NO

Table 12 Results of costs scenario 2, k=1

Moreover, the results in Table 12 disclose that the coalition is not stable, by any of the allocated methods, since savings are negative for all households as allocated costs from the coalition are greater than the individual costs from the non-cooperative model.

Following the simulation procedure, the steps are repeated with the new coalition to obtain a stable one in iteration k=1. A new coalition without household 3 is formed, {1,2,4}. The contracted power for this coalition is assumed to be lower than 10kW, and therefore tariff 2.0.A. is applied, both to the non-cooperative and cooperative models. The resulting contracted power after the optimisation is run for individual agents is the same in the stand-alone operation as in previous simulation, as agent 3 has left the coalition but the load profiles have not changed. However, in the cooperative model, because there is a different coalition, the contracted power is now verified to be lower than 10kW.

	Contracted power dp (kW)	**Tariff**	**Installed PV capacity (kW)**
Cooperative model	2,46 kW	2.0.A	1,3

Table 13 Changes in tariff for the cooperative model

The total cost of the coalition formed by the remaining three households is lower than their stand-alone operation.

$$C(S) = 855€ < \sum_n C_n = 897€$$

Economic benefits arise, as in scenario 1, from the common connection point to the grid reducing the grid cost terms and increasing the installed capacity of PV panels to self-generate as shown in Table 12.

The generation and consumption profiles for this stable coalition are plotted in Figure 10, a winter day 1st of January 2018 and in Figure 11 a summer day, 1st of July 2018.

Winter profile shows the higher energy production in the cooperative scenario than the non-cooperative, therefore less consumption from the grid (energy bought) respect to the individualistic model. Moreover, during the non-solar hours, the energy supply for both models is provided by the grid. The sale of energy is not beneficial for none of the models as obtained in the optimisation results.

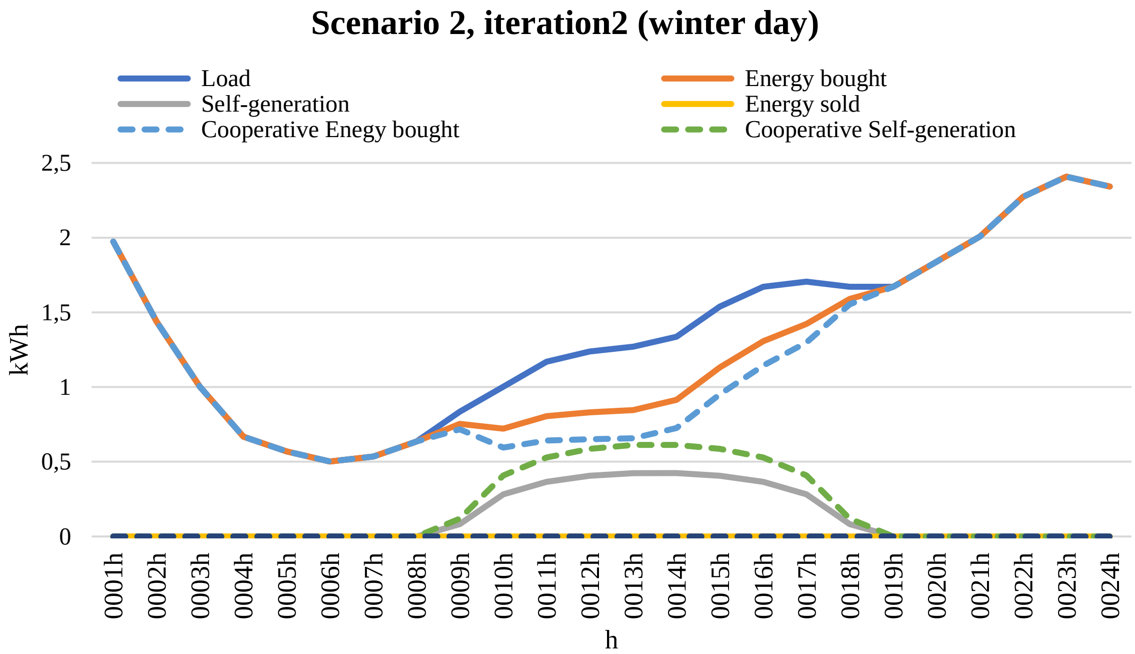

Figure 10 Generation and consumption profiles Scenario 2, winter day

The summer profile shows a lower energy demand of the community, and both the cooperative and non-cooperative models profit from the high production of the PV panels. The cooperative model generates and sells more energy than the non-cooperative model which buys more energy from the grid to supply its demand. The higher use of the energy grid to cover the demand is therefore repeated along the year for the individualistic model, which incurs in higher costs respect to the joint operation as shown in Table 16 General savings breakdown.

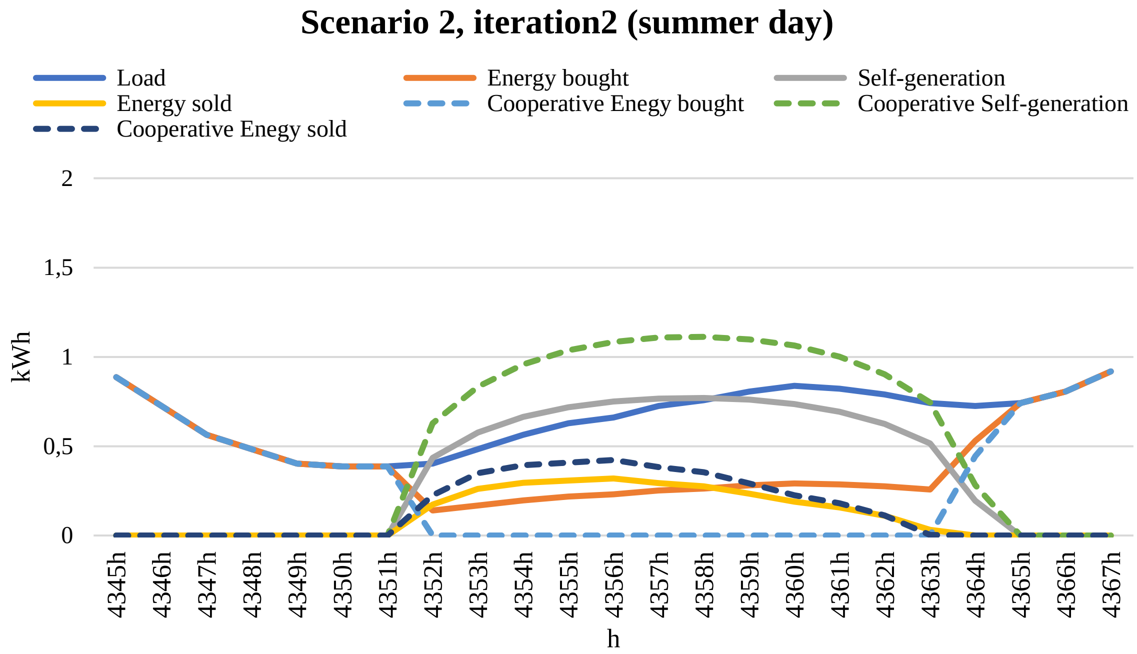

Figure 11 Generation and consumption profiles Scenario 2, summer day

Not only the global costs are reduced, but also each member of the new coalition {1,24} benefits from cooperating as it is shown in the results in Table 14, and therefore this coalition is stable, and the simulation procedure is stopped.

	Non-cooperative model costs (€)	**Cooperative model costs (€)**		**Savings**			
	C_n	γ_n	$\varphi_n(C,S)$	**Savings** $C_n - \gamma_n$	**Stay in coalition?**	**Savings** $C_n - \varphi_n(C,S)$	**Stay in coalition?**
H1	528	511	520	3,2%	YES	1,6%	YES
H2	105	88	78	16,0%	YES	26,0%	YES
H4	264	256	257	3,2%	YES	2,5%	YES

Table 14 Results of costs scenario 2, iteration 2

Savings allocated with the Shapley value, respect to the ones obtained depending on the demand profile, only benefit household 2 in this case. The main reason is that its marginal contribution to the general costs is very low as its demand is null during most of the winter months, when the electricity demand and so spot prices are higher. Furthermore, its investment in PV panels is null when operating as an individual agent as it can be seen in Table 12, so its low marginal cost due to this term also increases its allocated benefits when the Shapley value is calculated.

5.3 *RESULT ANALYSIS*

In this section following analysis of the obtained results from scenarios are approached:

- Comparison between the total costs of the energy community obtained with the cooperative model and the non-cooperative model.
- Comparison of individual costs obtained from the non-cooperative model and allocated costs with two distribution methods, from the cooperative model.

5.3.1 TOTAL COSTS

In the two scenarios simulated, the total cost of the coalition is reduced when it is stable, and all members within the coalition obtain benefit.

		Non-cooperative costs (€) $\sum_n C_n$	**Cooperative costs (€)** $C(S)$
Scenario 1	***Coalition {1,2,3,4}***	1266	1322
Scenario 2	***Coalition {1,2,3,4}***	3020	3302
	Coalition {1,2,4}	897	855

Table 15 General costs of both scenarios

In scenario 1, the economic benefit of the cooperation comes from the common connection point to the grid that reduces the cost of tariff paid in the cooperative model as well as the reduction of energy bought from the grid to supply the demand. This can be seen in the savings breakdown of Table 16 where the positive benefit from cooperation are originated in the reduction of payment of the grid fixed and variable terms (contracted power and energy bought from the grid). Moreover, the investment in technologies and energy autoconsumed is higher, also reducing the energy bought.

	Total Savings from cooperation				
	Contracted power	**Bought energy from the grid**	**Sold energy to the grind**	**Investment costs**	*Total*
Scenario 1	9%	10%	-1%	-31%	*4%*
Scenario 2: k=0	-13%	-7%	81%	-14%	*-9%*
Scenario 2: k=1	13%	12%	-23%	-44%	*5%*

Table 16 General savings breakdown

In the second scenario, when the demand of household 3 is increased, the tariff range of the cooperative model is surpassed, and the grid terms are more expensive resulting in higher cooperative costs as shown in Table 15. Therefore, in the cooperative model of this iteration, the coalition invests more in technologies to generate and autoconsume and avoid the increase of this tariff costs. The variable term of energy sold to the grid is also higher and this is the reason why the benefits reach up to 81%. Nevertheless, the total savings of cooperation are negative, so the households opt not to cooperate in this coalition and another coalition is formed.

Once the new coalition is formed in the second iteration of scenario 2, household 3 is excluded and the demand decreases entering tariff range 2.0.A. In this case the coalition is stable, and the cooperative situation brings economic savings. The investment costs however are again more expensive because the coalition invests more in technologies than individual households autoconsuming more. Grid charges are reduced due to less contracted power when cooperating (2.46kW<2.82kW).

5.3.2 INDIVIDUAL COSTS

Individual costs for each household, in the cooperative model, are allocated according to the Shapley value of cooperative game theory and according to the annual energy consumption of each household. The results of both distribution methods do not always turn out benefiting the same agents. The allocation depending on the energy consumed by each household only considers the sum of energy demanded and its percentage respect to the whole coalition consumption. The fair distribution according to the Shapley value, considers the marginal contribution of each agent to the coalition. This explains that if there is a parameter change that affects the cost function, for example the fixed term of the grid tariff, each household will have a different marginal contribution to the cost, depending on its peak demand of consumption and therefore its contracted power.

As remarked in the results of scenario 1 in Table 10, household 3 obtains less benefit from the Shapley distribution than from the annual consumption distribution. This is because although the peak demand of household 3 is approximately the same as household 1 (Table 4), its annual consumption is 26% lower than household 1. Therefore, when distributing the costs, there is a higher cost associated to household 3 for the contracted power of the coalition, but its annual demand is much lower than household 1.

Moreover, economic benefits from cooperation are more adequately distributed with the Shapley value because this method considers the implication in costs of agents on each possible coalition. Therefore, even though not all households benefit from this distribution as from the proportional one, it makes sense when a cooperative game is modelled to allocate costs accordingly.

Chapter 6 CONCLUSION AND FUTURE WORK

6.1 CONCLUSION

The economic results of the common energy management and investment of households in a community is analysed in this thesis. The cooperative model is compared to the individual operation to identify the possible benefits. The results show that supplementary demand profiles of different households provide a reduction in costs in the cooperative model, when the same tariff terms are applied, because the peaks do not coincide, and the contracted power is therefore lower than the sum of the individual ones. Moreover, when the same tariff terms are applied to the cooperative and non-cooperative models, households obtain economic benefits from cooperation. These benefits also arise from the sole connection point to the grid, diminishing the grid tariff cost. The supplementary use of the energy provide also advantages from the energy management point of view. The different load demands of each household varies their individual amount of savings, as their contribution to the total cost is directly dependent on their energy consumption. Once the total cost of the group is obtained, it has been allocated among the members of the coalition using the Shapley value from cooperative game theory and using an energy consumption proportional factor. These two methods of distribution of costs provide the individual savings for individual households that cooperate. These agents stay in the coalition when they obtain benefits from the allocated costs with respect to the individual operation and investment on their energy resources. The allocation using the Shapley value includes the individual contribution of costs of each agent to the whole coalition and therefore distributes more fairly the common value, rewarding or punishing accordingly to the increase in costs produced when each household joins. On the other hand, the distribution depending on the annual energy consumed by each household does not consider the impact of their individual cost on the overall cooperative cost. This is reflected when two households show similar peak demand but very different annual energy consumption, the corresponding Shapley value results similar for both agents but the cost allocated depending on the energy consumption method is very much different.

Moreover, in the scenarios studied both methods show the same stability results, all agents with benefits or all without, even though these benefits differ from the method used to distribute them. Finally, the economic benefits from cooperation can be increased including economies of scale if the number of households within the coalition is large and they can benefit from investment cost reductions. However, this has not been applied in the study, where all same investment costs have been used to analyse the effect of cooperation itself.

Altogether cooperation has been approached in this work only from an economic point of view but autonomy from the grid and sustainable energy production and efficient energy management are other benefits that can contribute to incentivise users to cooperate.

6.2 *FUTURE WORK*

Further research work related to the study of cooperation in energy communities can be carried out based on the following ideas:

- Increase the number of agents in the game to study the stability of different coalitions and understand the effect of larger energy communities.
- Vary load demands in time and joint or separate peaks to identify changes in the cost results.
- Include technical degradation parameters of the batteries. The technical parameters like the degradation of the battery can reflect benefits in the cooperation mode leading to a more efficient use of the batteries.
- Include other possible resources in the cooperation model such as electric vehicles.
- Include the cooperation between other energy communities to sell energy in the wholesale market and measure market power by means of cooperative game theory.
- Consider the impact of grid constraints

BIBLIOGRAPHY

[1] R. Héliot, «Energy Communities are reshaping the energy value chain», *Aster Cap.*, 2014.

[2] Ernesto Macías, «Día Internacional del Sol: es el tiempo del autoconsumo», 21-jun-2019.

[3] *Real Decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativas, técnicas y económicas del autoconsumo de energía eléctrica*. 2019.

[4] E. Espe, V. Potdar, y E. Chang, «Prosumer Communities and Relationships in Smart Grids: A Literature Review, Evolution and Future Directions», *Energies*, vol. 11, n.º 10, p. 2528, sep. 2018.

[5] X. Blot, «Is this a new golden-age for energy communities?», *World Econ. Forum*, 2018.

[6] M. Marzband, R. R. Ardeshiri, M. Moafi, y H. Uppal, «Distributed generation for economic benefit maximization through coalition formation-based game theory concept», *Int. Trans. Electr. Energy Syst.*, vol. 27, n.º 6, p. e2313, feb. 2017.

[7] W. Lee, L. Xiang, R. Schober, y V. W. S. Wong, «Direct Electricity Trading in Smart Grid: A Coalitional Game Analysis», *IEEE J. Sel. Areas Commun.*, vol. 32, n.º 7, pp. 1398–1411, jul. 2014.

[8] J. B. S. Fernández, «Desarrollo de un algoritmo de interrelación para microredes de distribución eléctrica», Master's Thesis, Universidad de Cuenca, Ecuador, 2015.

[9] W. Saad, Z. Han, H. V. Poor, y T. Basar, «Game Theoretic Methods for the Smart Grid», *CoRR*, vol. abs/1202.0452, 2012.

[10] W. Saad, Z. Han, y H. V. Poor, «Coalitional Game Theory for Cooperative Micro-Grid Distribution Networks», en *2011 IEEE International Conference on Communications Workshops (ICC)*, 2011.

[11] N. H. Son, «Using game theoretic approaches to implement smart grids», Master's Thesis, Macquarie University, 2016.

[12] A. Martínez Sánchez, «Aplicación de la teoría de juegos a la asignación de costes de red en el mercado de electricidad de la Unión Europea», Master's Thesis, ICAI-Universidad Pontificia Comillas, 2006.

[13] I. Abada, A. Ehrenmann, y X. Lambin, «On the viability of energy communities», 2017.

[14] E. Tveita, «Methods for Cost Allocation Among Prosumers and Consumers Using Cooperative Game Theory», Master's Thesis, Norwegian University of Science and Technology, 2018.

[15] Y. Wang, W. Saad, Z. Han, H. V. Poor, y T. Basar, «A Game-Theoretic Approach to Energy Trading in the Smart Grid», *IEEE Trans. Smart Grid*, vol. 5, n.º 3, pp. 1439–1450, may 2014.

[16] J. M. Zolezzi y H. Rudnick, «Transmission cost allocation by cooperative games and coalition formation», *IEEE Trans. Power Syst.*, vol. 17, n.º 4, pp. 1008–1015, nov. 2002.

[17] José Villar, «The next revolution in the energy sector: buy and sell of energy!», 29-may-2019.

[18] A. Chis y V. Koivunen, «Coalitional game based cost optimization of energy portfolio in smart grid communities», *ArXiv E-Prints*, may 2017.

[19] A. Barbato, A. Capone, L. Chen, F. Martignon, y S. Paris, «A power scheduling game for reducing the peak demand of residential users», en *2013 IEEE Online Conference on Green Communications (OnlineGreenComm)*, 2013.

[20] R. Verschae, T. Kato, y T. Matsuyama, «Energy Management in Prosumer Communities: A Coordinated Approach», *Energies*, vol. 9, n.º 7, p. 562, jul. 2016.

[21] B. Gao, W. Zhang, Y. Tang, M. Hu, M. Zhu, y H. Zhan, «Game-Theoretic Energy Management for Residential Users with Dischargeable Plug-in Electric Vehicles», *Energies*, vol. 7, n.º 11, pp. 7499–7518, nov. 2014.

[22] J. von Neumann, O. Morgenstern, H. W. Kuhn, y A. Rubinstein, *Theory of Games and Economic Behavior (60th Anniversary Commemorative Edition)*. Princeton University Press, 1944.

[23] Carlos Albert García, «Métodos de asignación de los costes de limpieza de un río y del reparto de agua», Universidad de Sevilla Escuela Superopr de Ingenieros Departamento de Matemática Aplicada, Sevilla, 2012.

[24] Alexander Kolker, «The Concept of the Shapley Value and the Cost Allocation Between Cooperating Participants», *Enciclopedia of Information Science and Technology*. jul-2017.

[25] «Proyecto Indel. Atlas de la demanda eléctrica española», Red Eléctricca de España. S. A., 1998.

[26] «Informe de precios energéticos regulados. Datos octubre de 2018.», IDAE.

[27] «https://www.esios.ree.es/es/pvpc».

[28] «Lazard's levelized cost of energy analysis- Version 12.0.», Lazard, 2018.

[29] «https://madridsolar.es/baterías-de-litio-lg/1367-batería-de-litio-lg-chem-resu-33-48v-33kwh.html?search_query=+bateria+litio&results=425». .

APPENDIX

Calculation Shapley value.

To obtain the Shapley value for each agent, the payoff of each possible coalition is calculated, simulating all coalitions in the cooperative model.

Scenario 1

Possible coalitions to be formed:

$$2^N = \begin{Bmatrix} \emptyset, \{1\}, \{2\}, \{3\}, \{4\}, \{1,2\}, \{1,3\}, \{1,4\}, \{2,3\}, \{2,4\}, \{3,4\}, \\ \{1,2,3\}, \{2,3,4\}, \{1,3,4\}, \{1,2,4\}, \{1,2,3,4\} \end{Bmatrix}$$

Each household can belong to the following coalitions:

$$S(1) = \{\{1\}, \{1,2\}, \{1,3\}, \{1,4\}, \{1,2,3\}, \{1,3,4\}, \{1,2,4\}, \{1,2,3,4\}\}$$
$$S(2) = \{\{2\}, \{1,2\}, \{2,3\}, \{2,4\}, \{1,2,3\}, \{2,3,4\}, \{1,2,4\}, \{1,2,3,4\}\}$$
$$S(3) = \{\{3\}, \{1,3\}, \{2,3\}, \{3,4\}, \{1,2,3\}, \{2,3,4\}, \{1,3,4\}, \{1,2,3,4\}\}$$
$$S(4) = \{\{4\}, \{1,4\}, \{2,4\}, \{3,4\}, \{2,3,4\}, \{1,3,4\}, \{1,2,4\}, \{1,2,3,4\}\}$$

The costs for each coalition are obtained from the optimisation model:

Coalition $S \subseteq N$	**Cost $C(S)$**
{}	0
{1}	528
{2}	105
{3}	425
{4}	264
{1,2}	592
{1,3}	939
{1,4}	792
{2,3}	496
{2,4}	331
{3,4}	678
{1,2,3}	1004
{2,3,4}	746
{1,3,4}	1202
{1,2,4}	855
{1,2,3,4}	1266

Table 17 Coalitions and payoffs scenario 1

Scenario 2, k=2

Same coalitions can be formed as in scenario 1 as the number of players remains constant.

New costs results:

Coalition $S \subseteq N$	Cost $C(S)$
{}	0
{1}	528
{2}	105
{3}	2123
{4}	264
{1,2}	658
{1,3}	2947
{1,4}	889
{2,3}	2468
{2,4}	366
{3,4}	2669
{1,2,3}	3021
{2,3,4}	2743
{1,3,4}	3229
{1,2,4}	953
{1,2,3,4}	3302

Table 18 Coalitions and payoffs scenario 2, k=0

Scenario 2, k=1

The number of players in the game is reduced to three. New posible coalitions:

$$2^N = \{ \emptyset, \{1\}, \{2\}, \{4\}, \{1,2\}, \{1,4\}, \{2,4\}, \{1,2,4\}\}$$

Coalition $S \subseteq N$	Cost $C(S)$
{}	0
{1}	528
{2}	105
{4}	264
{1,2}	592
{1,4}	792
{2,4}	331
{1,2,4}	855

Table 19 Coalitions and payoffs scenario 2, k=1