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Methodology to optimise electricity demand in the residential sector through efficient load management

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Abstract.

The current energy model requires a transformation based on a sustainable model that is accessible to all, focused on the needs of citizens and committed to climate change. Moreover, the rising cost of non-renewable energy sources, and the growing presence of distributed renewable generation, has a major impact on the electricity sector, creating the need to develop mechanisms to help manage energy demand in order to converge towards an efficient, emission-free electricity system that is responsible for the environment and future generations. The main motivation is the recent change in the regulation of electricity tariff systems and the introduction of time discriminations in the residential sector. Based on the previous need and supported by a survey to find out society's predisposition and sensitivity to demand management, this paper presents the methodology developed as an active demand-side management mechanism for residential consumers, considering their load shifting priorities and prioritising the use of renewable energy if possible, reducing grid energy consumption. In a nutshell, the use of a tool capable of helping consumers to regulate their energy consumption, analyse their consumption pattern and plan their domestic loads to obtain the lowest energy and economic impact is developed.

Key words. Active demand-side management, Load shedding, Energy optimisation, Renewable energy, Load prioritisation

1. Introduction

An energy model must satisfy and reconcile economic, social and environmental development without negatively affecting the growth of future generations in order to be considered sustainable [1]. However, the current energy model is deficient in all three respects. On the one hand, economic unsustainability is evidenced by rising electricity prices. Secondly, on the social level, it is manifested through household energy poverty, represented by low incomes, low energy efficiency in housing and high energy prices too, and finally, on the environmental level, as the use of less efficient energy sources is promoted. In addition, the negative impact of the COVID-19 pandemic has had global repercussions in the energy sector: the number of people with access to electricity in developing countries, such as Africa, which has been growing for years, appears to be declining, and the resulting deficit in developed governments means that more than 100 million people cannot pay their electricity bills [2].

At the legislative level, the European framework has promoted and encouraged sustainable development to obtain a more competitive and innovative economy, through research and the development of projects in the field of renewable energies, energy saving and efficiency, smart grids and the introduction of electric vehicles [3]. Specifically, in Spain, methods of economic and financial sustainability were introduced through charges and tolls, and new obligations for self-consumption and renewable energy generation were defined through Law 24/2013 on the electricity sector [4]. Subsequently, new measures were incorporated through Royal Decree 244/2019 and Circular 3/2020, which represent a step forward for self-consumption, as well as an indirect resource for the promotion of energy efficiency and savings through the active participation of consumers [5] [6].

Encouraging efficient energy consumption in households by helping individual consumers to shift consumption from peak hours to other periods with excess generation is a key factor for the new energy model. Residential sector involvement in the energy context is important due to the fact that it is attributed with a demand of approximately 25% of electricity consumption in Spain [7], while building consumption accounts for approximately 40% of energy consumption in Europe [8]. The main challenges facing demand management are the reduction of the peak period of the demand curve, the integration of renewable energies and the promotion of active participation of consumers in active demand management [9]. This can be seen evidenced in the 2019 electricity yearbook, the maximum annual energy demand occurred in the month of January between 20 and 21 hours, with most of the consumption given by the residential sector with 34.5% of the total demand [10].

Some projects have previously been developed and implemented to provide consumers with information on how to manage electricity consumption. However, a project that brings together renewable generation and consumer priorities, trying to match the generation and consumption curve, has not yet been implemented. These projects serve as a basis for the development of subsequent projects. Table 1 shows some of these projects that have influenced the development of this methodology.

Table I. - Previous projects on demand management in the residential sector

Active demand management project	Country of application	Objectives
[11] Energy-Smart Pricing Plan (ESPP)	EEUU (2004)	Identify the response of residential consumers to hourly prices imposed by the electricity market, type of actions taken by consumers and definition of the magnitude of the effect.
[12] GAD Project: Active Demand Management	Spain (2010)	Research and development of tools to help reduce the consumer's electricity bill, the search for devices to inform the user of the price and origin of energy.
[13] Newmarket Hydro Time-of-Use Pricing Pilot	Canada (2008)	Provide consumers with information on how to manage electricity consumption by shifting the use of appliances to off-peak periods.

2. Methodology and application case for active demand management in the residential sector

A. Active consumer management for the reduction of energy consumption in households

The potential to manage demand is a complex process which depends on the sector in which the user is located and the flexibility it allows, thus, the residential sector offers more versatility to act on the demand curve than the industrial or services sector [14]. In the new energy model, the consumer adopts the key role of prosumer, participating and being aware of his or her role in the energy transition and becoming actively involved in demand management [15].

After conducting a survey on the basic concepts of demand management at the residential level and the awareness and willingness to change habits to achieve energy and economic savings, crucial results were obtained for the development of the methodology. Mainly, it was possible to conclude that more than 80% of those surveyed would be willing to change their habits to achieve electricity and energy savings, and 93.2% stated that they could adopt measures to reduce consumption in their daily routine if they were advised to do so. This information forms the basis for the development of a methodology that aims to help, advise and encourage society to adopt habits that are beneficial to themselves and the electricity system. It also incorporates the possibility of adapting it and making it more flexible according to the end user's priorities, making it an active demand management mechanism.

B. Development of the methodology for active demand management in the residential sector

Considering the results obtained from the survey, as well as the identified need to address the energy transition, the main aim of the methodology is to reduce the energy consumption from the grid, providing assistance to residential consumers to identify their consumption profiles, analyse them and plan their loads with the lowest energy impact.

The methodology aims to create a tool that shows small consumers how to use energy and helps them in sustainable energy planning, whether they are consumers of energy from the grid or prosumers who self-consume their own energy. It also allows the consumer to identify their consumption pattern, analyse it and plan their loads with the lowest energy and economic impact. Through the methodology, the role of the consumer is empowered, as it establishes consumption priorities, introduces the hours of use of appliances, enables consumption to be shifted from peak to off-peak hours and, in short, involves them in a more efficient use of the resources available to them in the home. The main mechanisms for achieving this are shown in the figure 1.

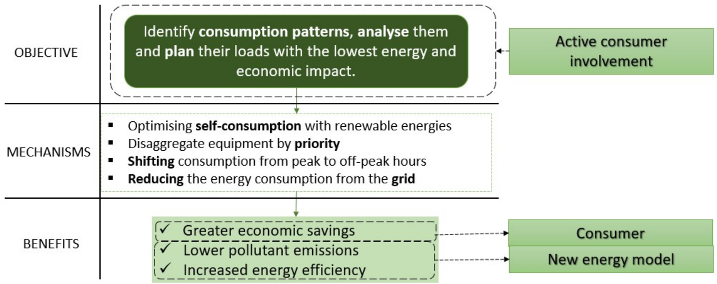

Fig. 1. Objectives, mechanisms and benefits of the methodology

The main focus of application of this methodology is a house with self-consumption technologies and with energy surplus under compensation. The input parameters necessary to optimise energy consumption and obtain results are:

- History of energy demand of the dwelling.
- History of energy generation produced for the dwelling.
- Updated energy prices.
- Priorities in the use of household appliances, to be defined by the user.
- Characteristics of generation and storage technologies (if applicable).
- Type of electricity rate (mainly for the Voluntary Price for Small Consumers - PVPC).

Involving all the variables and considering the current regulations, it is proposed to carry out an energy optimisation in order to reduce the energy consumption of the dwelling and, consequently, to reduce the cost of the electricity bill. The scheme presented in the following illustration summarises the input variables involved which, operating in accordance with the optimisation algorithms that will be shown below, will yield measurable results through economic and energy indicators.

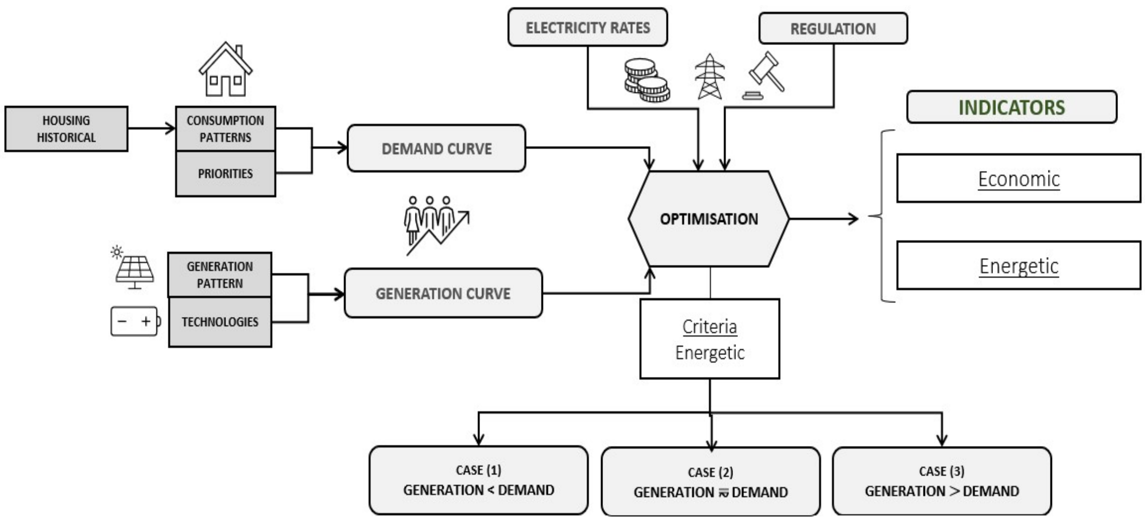

Fig.2 Interaction between the parameters of the methodology

C. Indicators and output parameters

Indicators are defined to assess the results obtained after the implementation of the methodology in a dwelling, as well as the effectiveness of the strategies taken or each of the mechanisms adopted. They can be divided into the following:

- **Economic: Savings on energy purchases (%).** The economic indicator calculates the cost savings of the energy demand supplied through the electricity grid at the price set by the trading company.
- **Energy: use of renewable energy (%).** The main objective of this indicator is to determine the percentage of demand supplied by renewable energy. If the dwelling does not have renewable energy sources, this indicator would not be applicable.

The output parameters of the algorithm implementation are the use of each strategy or mechanism (%), the demand supplied per period (%), and the purchase and sale of energy (€). In addition, to facilitate the consumer's understanding, a table of usage schedules for each appliance and a graph of the energy demanded will also be provided.

D. Optimisation criteria and algorithms developed

The methodology consists of an optimisation method that will be carried out on an hourly basis and depending on the values obtained from the historical demand data variables and the hourly generation produced by the installation, one of the three cases defined below may occur:

Table II. - Possible time cases in the hourly optimisation

Case 1	Generation < Demand	The generation pattern (PG) has lower values than the demand pattern (PD) for that hour. Instantly only part of the demand can be supplied and it should be studied whether there is energy stored in the batteries to supply the demand completely.
Case 2	Generation ≈ Demand	When the generation pattern (PG) has similar values to those of the user's demand pattern (PD) for the hour under study, the demand may be fully supplied but there will be no energy surplus.
Case 3	Generation > Demand	The generation pattern (PG) has higher values than the demand pattern (PD) for that hour. In this case the consumer's demand can be fully supplied and there will be a surplus of energy.

Once the cases in table 2 have been established, they are represented in the figures below. The diagrams presented lead to the implementation algorithm of the methodology, which will be executed on an hourly basis, so the optimisation must be carried out for each of the hours of the day, according to the consumer's priorities for each hour and the energy price established according to the electricity market.

In the first case, in which the generation of renewable energy is lower than the demand of the dwelling, if the dwelling has batteries, the energy available in them will be used and, if this is not sufficient, depending on the priorities given by the consumer, the equipment with the highest priorities will be supplied. Equipment that could not be switched on will be shifted to times when there is a surplus in the batteries and also when the consumer is willing to use them. Finally, if devices cannot be moved either because there is no surplus or because the consumer does not allow it, energy will be purchased from the grid. If generation is approximately equal to demand, no measures will be taken.

In the latter case, where there is surplus energy and demand is fully covered, the main measures will be, firstly, charging of the batteries. If surplus energy continues to exist, secondary consumption defined by the user will be supplied and, finally, energy will be fed into the grid with the consequent economic remuneration. Secondary consumptions shall be introduced only if the consumer considers it necessary.

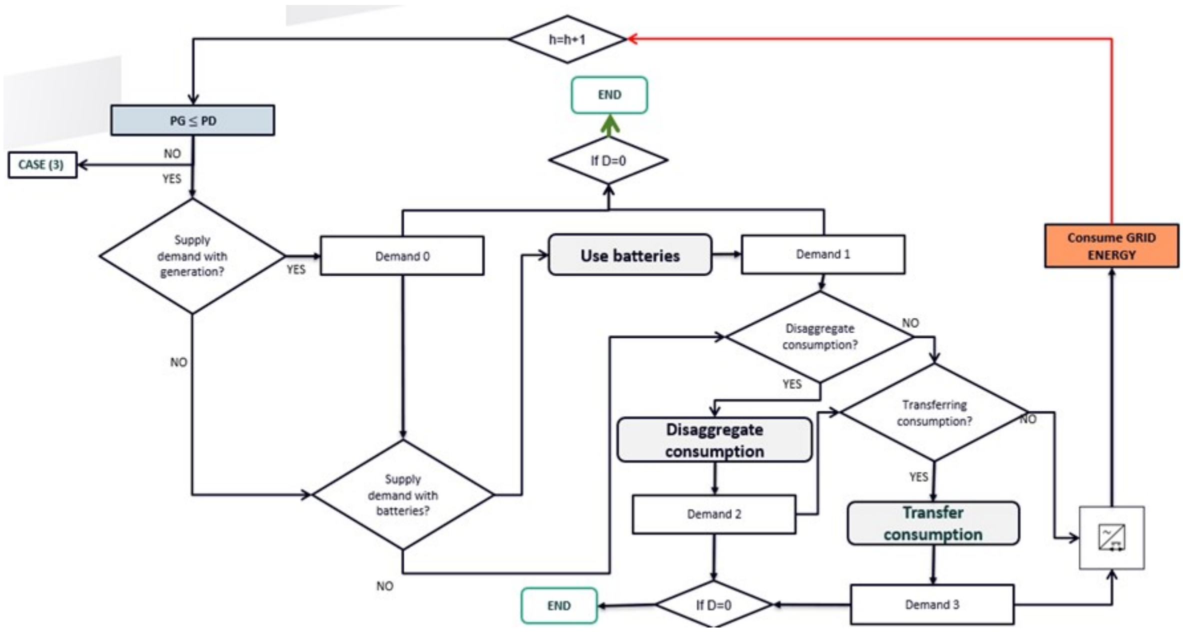

Fig.3 Operating algorithm for cases 1 and 2

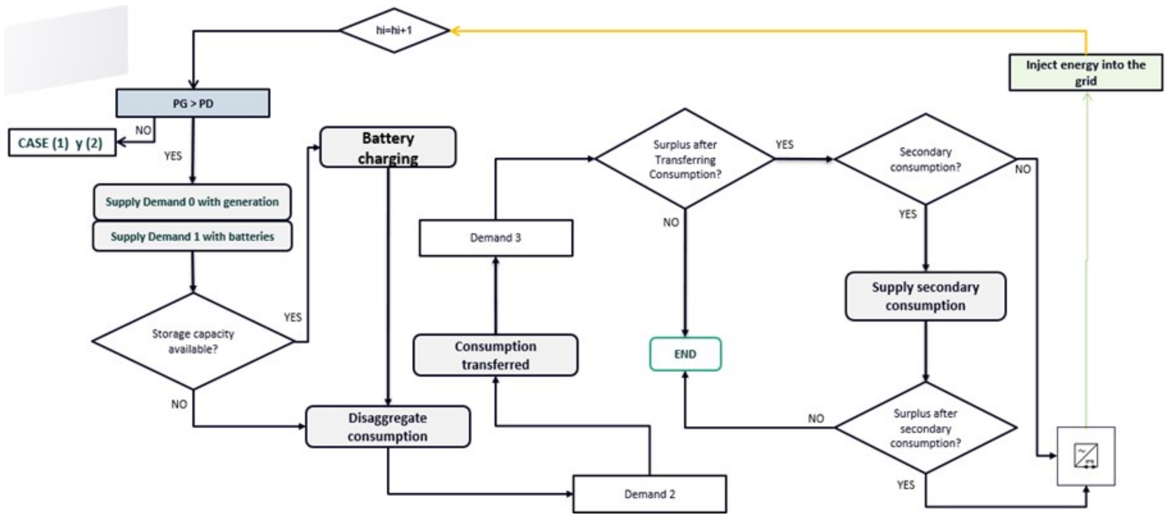

Fig.4. Operating algorithm for case 3

E. Application case in a self-consumption house

In order to evaluate the algorithm developed in the methodology, a case study was carried out on a single-family house with self-consumption located in a municipality in the Valencian Community (Spain).

The house has photovoltaic modules on the roof to generate electricity, as well as a lead-acid battery storage system. With regard to economic terms, the house has an Orbis smart meter installed by the distributor. The specific information is shown in the following table:

Table III. - Case study: specific input parameters

Type of Data	**Input parameter**	**Caste study data**
Economic data	Type of installation	Self-consumption with surpluses with compensation.
		Contracted power: P1=5,5kW P2=5,5kW
	Tariff group	2.0TD
Energy data	Energy demand (PD)	History obtained from I-DE energy [16]
	Generation profile (PG)	Irradiance history for location (39.537, -0.632) obtained from PVGIS [17] Photovoltaic modules: Peak Power: 1.8 kWp, Efficiency 18%.
	Storage Technologies	Maximum capacity: 150 Ah Depth of discharge: 40%.
	User preferences	Appliances, power, times of use, priority and transferability entered in the tool.

3. Results

Once the methodology has been applied to the case study, it will be analysed for a winter and summer working day (WD), and for a winter and summer holiday (HD), as consumption profiles vary accordingly. The prioritisation of appliances was introduced by the user.

As an energy indicator, the supply of demand through the use of renewable technologies is analysed. It is obtained that the use of batteries allows more than 30% of the demand to be supplied with renewable energies, making the use of the energy generated more flexible, even in the most unfavorable cases of winter. Furthermore, the maximum demand supplied with renewable generation was 96%, while the minimum was 38% for the unfavourable day, which means that these are very acceptable values. The table below shows the results obtained for the energy indicator.

Table IV. - Energy indicator: results obtained.

Proposed measures		SUMMER		WINTER	
		WD	HD	WD	HD
Renewable source	**Generation**	57%	63%	18%	5%
	Batteries	30%	32%	30%	30%
	Disaggregate	0%	0%	3%	3%
	Trans. Batteries	1%	1%	0%	0%
Total renewable		88%	96%	51%	38%
Purchase Grid		12%	4%	49%	62%

As for the economic indicator, table V shows the saving produced in the electricity bill after the application of the methodology. It can be deduced that, through the use of batteries, the saving values are very high, the minimum value being a saving of more than half of the purchase cost for the study day. Achieving savings of more than 50% under unfavorable conditions is a great achievement, since under good conditions the demand could be almost fully supplied.

Table V. - Economic indicator: results obtained.

SUMMER		WINTER	
WD	HD	WD	HD
94,98%	95,97%	55,66%	46,98%

Finally, it could be stated that this represents an average saving of more than 70% in the purchase of energy from the electricity grid for the home.

4. Conclusions

• The new energy model assigns a key role in the active management of energy demand to the domestic consumer. Awareness raising, clear information and advice for the adoption of sustainable habits should be promoted.
• This paper presents the development of a methodology based on sustainable scenarios adapted to the specific priorities of each household consumer.
• The methodology allows economic savings on electricity bills, greater energy efficiency and a reduction in pollutant emissions. The use of renewable energies to supply demand is optimised, reaching a minimum of 38% for the most unfavourable winter day. In additions, it supposes an average annual saving of 70% on the electricity bill.
• There is the possibility of integrating this type of tool in smart homes for demand management.

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