Incentive-based demand response: Case study

Respuesta de la Demanda Basado en Incentivos: Caso de Estudio

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Abstract— **The present article discusses the development of a demand response system on a residential setting given that the proper management of energy resources by users can solve scarcity and energy reliability issues. The behavior of 1000 residential users is modelled through a peak control program based on economic and energy-related incentives. A demand response (DR) application is used where remuneration depends on scarcity pricing. The case study is shown including a mathematic algorithm and the application. The results obtained with the application exhibit a reduction of energy peaks, which translates into more efficient energy management which in turn is remunerated by scarcity pricing. It is concluded that the incentive-based DR program is viable both energy-wise and financially.**

Index Terms— **Aggregator; Demand Response (DR); Incentives; Optimization; Scarcity Pricing.**

Resumen— **El presente artículo pretende desarrollar la Respuesta de la demanda a nivel residencial, dado que con la adecuada gestión energética de los usuarios, se puede resolver problema de escasez y confiabilidad energética. Para esto se modela el comportamiento de mil usuarios residenciales al aplicar un programa de control de picos basado en incentivos energéticos y económicos por medio de un aplicativo de respuesta de la demanda (RD), donde la remuneración se realiza en función al precio de escasez. Se presenta el caso de estudio, el algoritmo matemático implementado y el aplicativo. En los resultados obtenidos en el aplicativo se tiene la disminución de los picos de energía, lo que representa una mejor gestión de energía, esta a su vez se ve remunerada por el precio de escasez, lo que permite concluir que el programa de RD basado en incentivos de control de picos es viable energética y económicamente.**

Palabras claves: Agregador, Incentivos, Optimización, Precio de escasez, Respuesta de la demanda (RD).

I. INTRODUCTION

HALFWAY through 2016, Colombia suffered harsh consequences from the climatic event known as the El Niño phenomenon. This recurring weather pattern implies changes in temperature of waters in Central and Eastern regions of the Pacific tropic, directly affecting the distribution of precipitations in tropical areas [1]. This phenomenon caused droughts in the reservoirs of the country and led to an energetic crisis, prompting the "apagar-paga" campaign [2] (in Spanish, "it pays off to turn off") based on incentives and penalizations for commercial and residential users to manage energy demands. It is expected that the demand response program improves the energy management to mitigate the aforementioned problems.

Demand response (DR) is defined as a set of strategies seeking to reduce the demand-related peaks from different participants of the energy market through the use of incentives or penalizations [3], [4], [5], [6]. A review of the scientific literature shows that the demand response of the residential sector based on incentives is a viable solution for the electrical system while handling scarcity issues and reducing demand-related peaks [7], [8]. Each user can contribute with a determined amount of manageable power [9], [10], [11] that he/she is willing to unplug or reduce during certain hours of the day. This depends on a set of requirements given by the network operator, distributor or demand aggregator [12].

In [13], the integration of residential DR as an efficient strategy to balance the offer and demand of energy is studied. The authors in [14] present control and automation models suitable for users. In [15], it is proposed that the design of DR programs includes a multi-agent system with an aggregator that sets rules for users. The article in [16] shows that smart grids combined with distributed generation allow a complete integration with users through proper automation. The establishment of agreements in the form of 'disconnection contracts' leads to a stable power disconnection offer [17]. Demand peaks are also reduced compared to price-based DR [4], [18], translating into economic benefits for energy distributors since energy in peak hours is more expensive in both in terms of price and the environment. The latter is related to the activation of thermal power plants to cover the excess in demand.

A case study is presented that serves as an example of the applicability of the DR resources based on incentives, compensated by using the scarcity pricing mechanism in the presence of demand-related peaks. It is proposed to unplug a share of the manageable power from 1000 residential users of middle income in the city of Bogotá, Colombia. A software application is developed that assesses the energy consumption per hour and the behavior of the global demand curve of users participating in DR incentive-based peak control services within a distribution network. The application can calculate the global cost of the energy not consumed by users and determine the shape of the consumption curve once the DR strategy is activated.

II. METHODOLOGY

Fig. 1 represents a block diagram of the methodology used for the development of the case study. In first place, a conceptual framework of DR programs is defined in terms of peak demand control, scarcity pricing, user demand curve and manageable load. In second place, the case study is described as well as the variables and the mathematic reasoning behind the application used to simulate the DR program. The results and their analysis are shown in the final section.
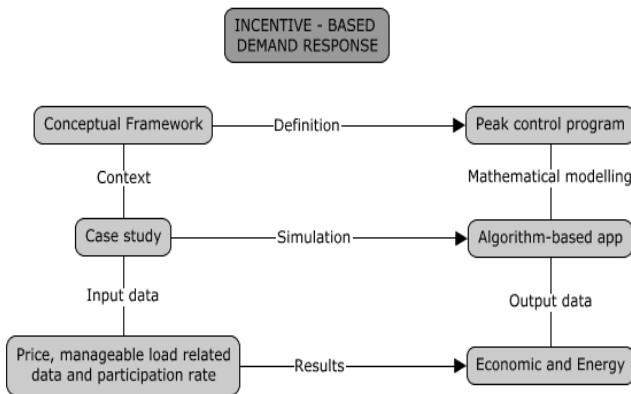

Fig. 1. Methodology diagram. Source: Author.
Program: CMAPTOOLS.

III. CONCEPTUAL FRAMEWORK

This article applies the incentive-based demand response (DR) program whose advantages and disadvantages are listed in *TABLE* . According to [4], [5], [6], this technique can reduce the energy peaks of the user demand curves, by remunerating the aggregator with the scarcity price of the unplugged manageable load.

TABLE I
ADVANTAGES AND DISADVANTAGES OF INCENTIVE-BASED DR

Advantages	Disadvantages
As the programs maintain growth, the partial control of most of the national demand can be achieved.	The strategies for the reduction of demand curve have an effect on a long term basis.
The disconnection of the demand is mandatory so the aggregator ensures a minimum amount of energy to offer.	There is an involuntary participation of the provider in some programs.
It is not necessary to change the charging fee to a time-based system.	It has more robust control system compared to the pricing strategy which makes it more expensive
Ideal for demand-related peak reduction.	It is not ideal for overall flattening of the demand curve, i.e. reduce consumption
Ideal for cheap and reliable markets.	The public needs to be convinced to participate in these programs.

A. DR in peak demand control

Incentive-based DR programs that include peak control operate by remotely cutting power supply when the system considers it to be convenient. This improves the reliability of the system during high-demand timeslots and negotiates beforehand the energy cuts through contracts or load reduction. Peak control programs can be implemented with voluntary cuts or automation-based mandatory cuts.

B. Scarcity pricing

These prices are established by the Colombian entity known as CREG (Energy and Gas Regulation Commission) which updates said prices each month [18] based on the variation of the fuel price index "New York Harbor Residual Fuel Oil 1% Sulfur LP Spot Price". The scarcity price has a double purpose: it indicates when firm energy obligations are required "When the price surpasses the scarcity price" and it is also the price in which the supplied energy is compensated when said obligations are required [19]. In December 2018, the scarcity price stood at 0.16 dollars [20].

C. User demand curve

The demand curve, hourly or load-based, is a graphical representation of the electric demand throughout time [21]. According to international parameters, a minimum demand of 100 kW must be satisfied each hour in order to participate in demand response programs [22]. Hence, the typified demand curve is assessed as a case study for residential type consumers of middle socio-economic strata. The curve was defined by the GCEM research group from Universidad Distrital Francisco José de Caldas, based on consumption monitoring and polls answered by users [12]. Fig. 3 corresponds to the typified demand curve for a middle-class user.
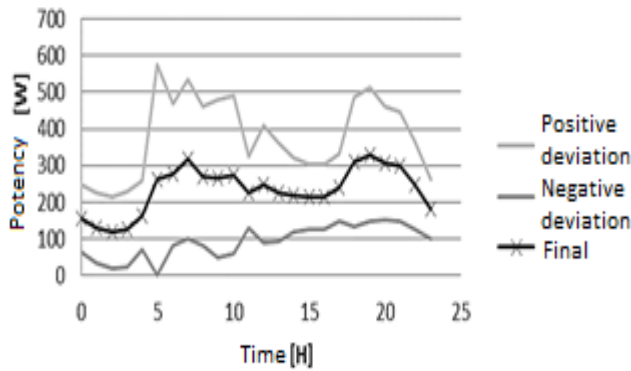
Fig. 2. User demand curve for a middle strata user in Bogotá. Source: GCEM Group Universidad Distrital Francisco José de Caldas.

Fig. 2 shows that the periods of higher consumption are between 6:00 and 9:00 and between 18:00 and 21:00.

D. Manageable load

In this work, a manageable load is defined as the amount of power to be disconnected in a DR program. In some countries such as Singapore [23], current legislation sets the manageable load at 10%. For other authors [22], the manageable power percentage can reach 10, 20 or even 30%, which is more suitable to study the effects of DR programs. In Colombia, it is difficult to know the actual percentage of these types of loads since DR has been introduced quite recently. However, there is a precedent that serves as a reference point which is the "Apagar-paga" campaign that allowed the country to save 6.4% of energy in six weeks [2]. For the real scenario, it is recommended to use the 10% value for manageable loads. For academic and representative purposes, the load to be unplugged is set at 30% of the total load. In the case of dispatch, this value can reach 50% due to the existing timeframes (time period divisions throughout the day) which diminish the hours of the day when energy can be offered. There are four timeframes of 6 hours each and users can be present in two of them.

IV. CASE STUDY

A case study consisting of 1000 users was proposed as a testing scenario. Their energy consumption behavior (demand curve) corresponds to the middle income strata of the city of Bogotá. The participation of users is made mandatory through contracts, thus the participation rate is 100%. The program is called peak control since it consists on the direct reduction of high energy consumption during specific timeslots by 30% (manageable load). This energy disconnection is compensated based on the scarcity fee in dollars. The purpose is to analyze the energy-wise and economic advantages by applying the peak control program within a simulation. The peak control algorithm details the mathematical component of service operation, the application and the expected results of said service over the demand curve. The amount of disconnected energy and service cost (earnings from daily energy disconnection) are also defined.

A. Peak control algorithm

In this program, the input data for the aggregator are the scarcity price (Pe) in dollars (USD) and the manageable percentage (Pg) given in p.u. For users, the input data are the demand curves $(D(h))$ where the independent variable is the hours (h) and the dependent variable is the power consumed by the user in kW. Users are represented by the letter (u). Peak hours are 6 to 9 am and 6 to 9 pm labelled with (hp_{on}) at the beginning of the timeframe and (hp_{off}) when it is over.

After inserting all the input values, the total demand $(D_T(h))$ is calculated as a function where the independent variable are the hours and the dependent variable is the joint demand from all user groups.

$$D_T(h) = \sum_{i=1}^{u} D(h) \tag{1}$$

The manageable load is computed as the total disconnection value of the service among all users (only during peak hours).

$$Cg(h) = Pg * D_T(h); \qquad hp_{on} \leq h \leq hp_{off} \tag{2}$$

The applied service curve $Cs(h)$ is derived from subtracting $Cg(h)$ from $D(h)$ in each user and from the global form of the sum.

$$Cs(h) = D_T(h) - Cg(h); \qquad hp_{on} \leq h \leq hp_{off} \tag{3}$$

To calculate the constant value of the dispatched energy (Cg), the entire manageable load is summed up according to the peak hours in which each user was cut off from service.

$$Cg = \sum_{hp_{on1}}^{hp_{off1}} Cg(h) + \sum_{hp_{off1}}^{hp_{off2}} Cg(h) \tag{4}$$

The last calculation pertains to the constant value of the service cost (Cs) which is obtained by multiplying the dispatched energy (Cg) with the scarcity price (Pe).

$$Cs = Pe * Cg \tag{5}$$

demand curves (after the peak control program), dispatched energy and earnings of the aggregator from said energy.
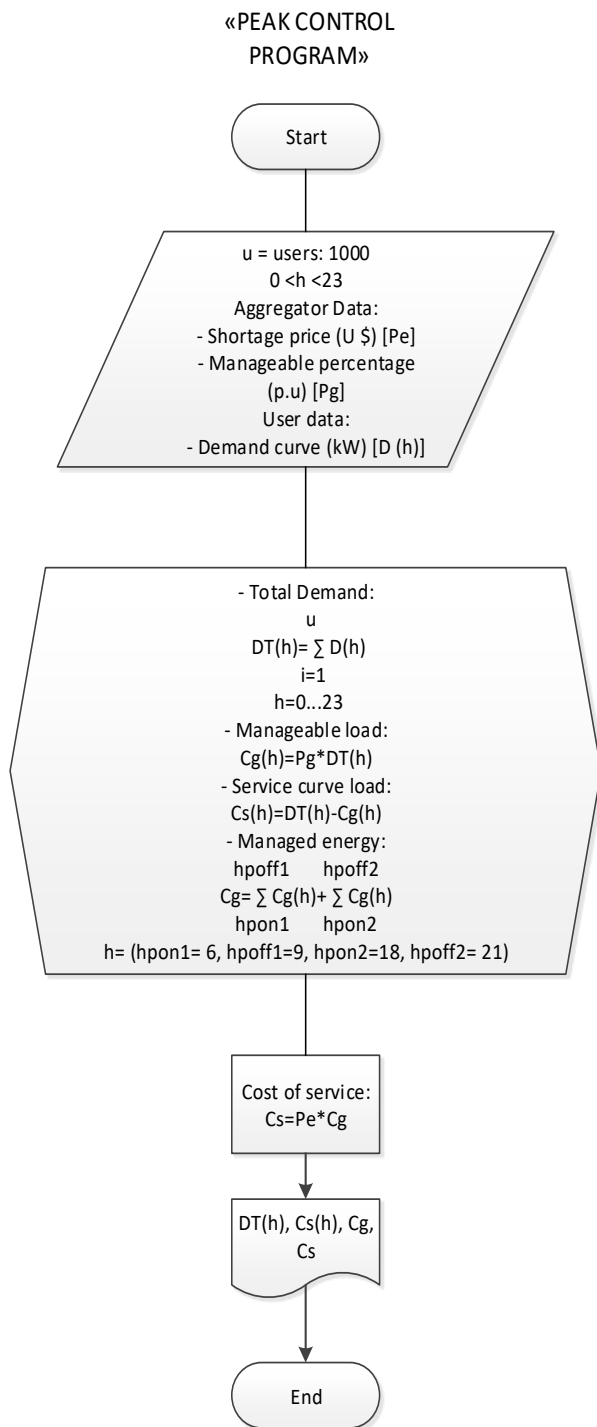

Fig. *3* corresponds to the algorithm of the main peak control program.

B. *DR program application for peak control*

Based on the proposed mathematic algorithm a software application was developed in MATLAB 2016 and Microsoft Excel 2013. It can simulate the demand response program for peak control. The input values received by the app are the scarcity price, the percentage of manageable load and the user participation rate. The output values are the initial and final
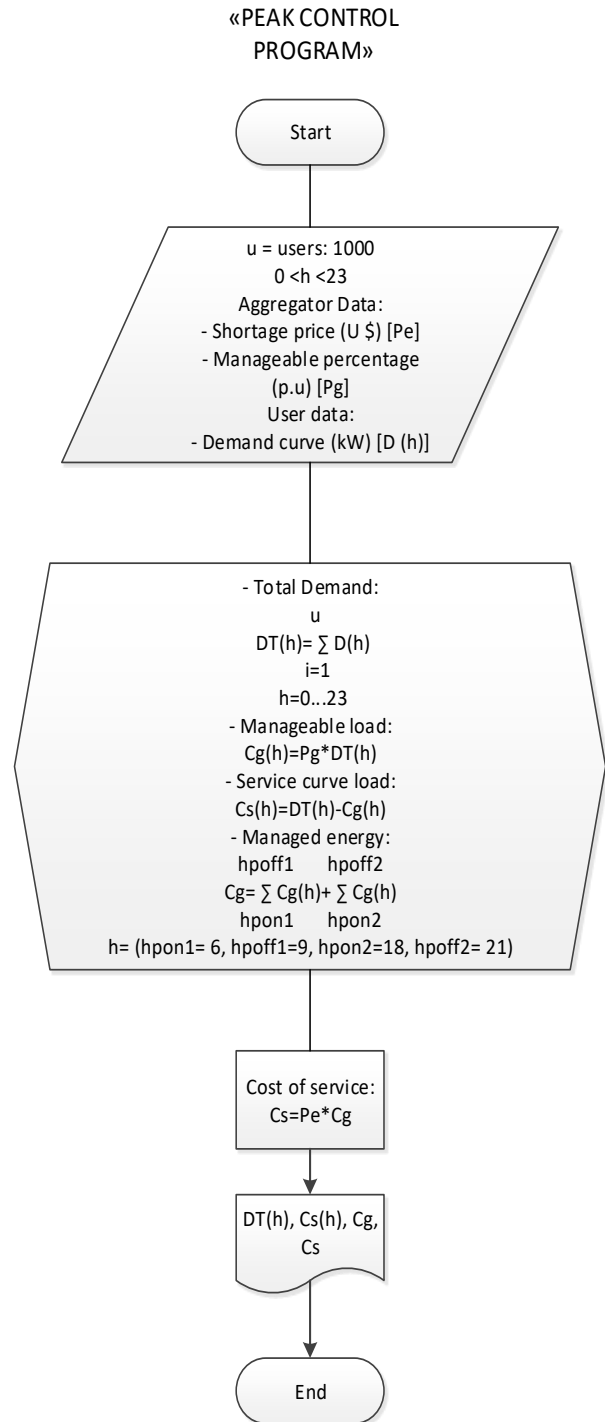

Fig. 3. Algorithm of the DR peak control program Source: Source: Author. Program: MICROSOFT VISIO.

V. RESULTS

In this section, the values obtained with the application are discussed according to the proposed study and the simulation. TABLE shows the input values inserted in the application (price, manageable load and participation rate). Afterwards, the results are assessed in terms of energy (changes in the demand curve regarding peak reduction and daily disconnected energy) and earnings in dollars.

TABLE II
INPUT DATA OF THE APPLICATION

Price	0,15 [USD]
Manageable load	30 %
Participation rate	100 %

The simulation results of the proposed application are presented based on the input values. The application plots the initial and final curves and delivers the values of disconnected energy and the net value received by the aggregator from daily savings. The results are then grouped for energy-related and economic analysis.

The results of the peak control program according to the case study can be evidence by comparing Fig. *4* with *Fig. 5*. The latter shows the peak disconnection, the disconnected energy and the changes in the demand curve. *Fig. 6* shows a daily disconnected energy of 711,812 kWh directly from the application, valued with a daily scarcity price of 106,722 USD.
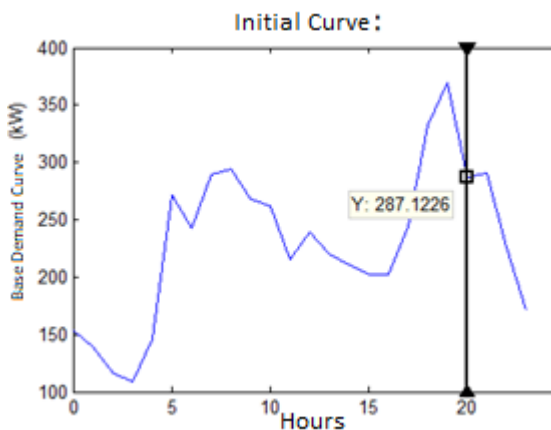

Fig. 4. Initial plot of 1000 users before the application of the DR program. Source: Demand response application, elaborated by author.
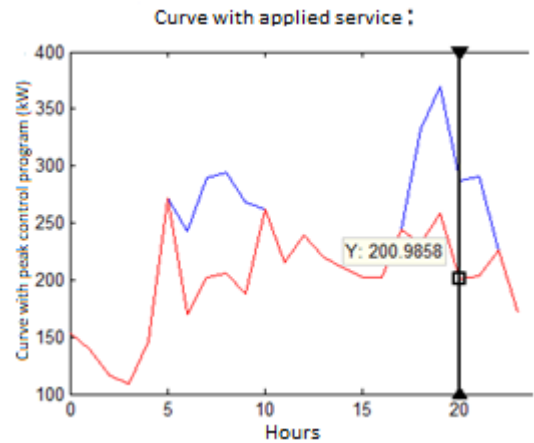

Fig. 5. Final plot of 1000 users after the application of the DR program. Source: Demand response application, elaborated by author.
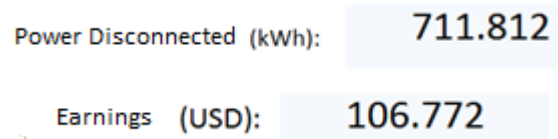

Fig. 6. Results of the peak control program. Source: Demand response application, elaborated by author.

TABLE III shows the results obtained including the input values of the disconnected energy in kWh, the earnings per day in dollars and the behavioral change in the user consumption curve for the described case study.

TABLE III.
PEAK CONTROL PROGRAM CONSOLIDATED RESULTS.

Disconnected energy	711.812 [kWh]
Earnings	106.722 [USD]
Behavioral change with the DR program	Elimination of energy peaks during higher consumption timeframes.

VI. ANALYSIS OF RESULTS

A demand response program structure is proposed that can be applied on an international scale given that it uses incentives during peak hours to directly reduce consumption. This solution is viable from a financial standpoint and can improve the quality of energy. A normative study of the country must be considered for the applicability of this type of program, thus allowing the adaptation of theoretical concepts in the practical field.

The value of the net daily income of the aggregator due to the energy disconnection (711.812 kWh), remunerated with a scarcity price of 106,722 USD. If this value is multiplied by the number of days in a year then the annual net income would be 38.953,53 dollars which is high given that the simulation only included 1000 users. Hence, the demand response program is clearly profitable in Colombia. There are additional benefits such as saving energy in Colombian households and automated houses (which is a requirement to apply the peak control program), while improving the comfort of users. The economic benefits of an energy network with higher quality

should also be considered, represented by a demand curve without consumption peaks.

The value of the demand response strategy is mainly evidenced in the linearization of the demand curve by cutting the consumption peaks. This causes the network to become more stable and less dependent on fossil fuel energy sources since thermal generation is used to cover up energy peaks. The resulting energy matrix is more environmentally friendly. Another advantage in terms of energy is the direct reduction of energy consumption with a daily saving of 711,812 kWh, which is an annual saving of 260 MWh. This energy saving allows a better distribution of the resources for generation and energy transportation. Therefore, the network is more flexible to supply energy in case of scarcity due to natural causes.

VII. Conclusion

The proposed program "Energy consumption modelled based on the middle-level strata in the city of Bogotá" with 1000 users and a manageable load of 30% (case study), delivers an annual energy disconnection of 260 MWh with 1000 users. The annual income for the aggregator is 38953,53 dollars, benefits for users (automation and energy savings) and benefits for the network (linear demand curve and better energy management). These results lead to conclude that the incentive-based DR peak control program is viable from an economic and energy standpoint and can be applied in international contexts.

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