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OPTIMIZATION MODEL TO MINIMIZE ELECTRICITY BUDGET SUBSIDIES.

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ABSTRACT

This research formulates an optimization model to minimize budget subsidies in the design of a cross-subsidy system for the electricity sector. The optimization problem of designing a cross-subsidy system is defined as a Mixed Integer Non-linear Programming problem since it involves the product of the decision variables; as well as any non-linearities proper to the functions representing the price and the electricity demand. Complexities in solving this problem can be simplified by considering average prices and average demand as given. The non-linear problem reduces to determining subsidy factors, contribution factors, size of the subsidized groups and size of the contributing groups. The optimization model presented in this research has been successfully applied to the electricity sector in Colombia to determine alternatives that do not require budget subsidies and provide full subsidies to customers in the first income decile for whom electricity bill could represent 90% of household income. Colombia provides electricity subsidies to 90% of residential customers, but the cross-subsidy system under collects requiring budget subsidies from the government. These budget subsidies have been increasing over the years. Therefore, the relevance of advocating the use of optimization models like the one presented in this research for the efficient allocation of resources. However, additional research studies are needed to test the applicability of these models in more real-life cases to promote their widespread usage in the design of energy policies.

Keywords:
Electricity tariffs; cross-subsidy; budget subsidy; optimization model; deregulated electricity sector; Colombia.

INTRODUCTION

Electricity consumption is a random variable that varies depending on the time of the day, day of the week, time of the year, region in a country among other things [1-8]. However, macro-level optimization models applied to the electricity sector [1-13] often consider simplifications to make the problem more manageable and less complex. These simplifications could include considering the demand as deterministic and the electricity price as given. Deterministic demand is usually set at a peaklevel since this generally represents the worst-case scenario [1-8]. Another alternative is to consider average values for these quantities [9-13]. Stochastic random demand can also be considered in the analysis by using demand scenarios generated randomly [7] or by representative future conditions [14]. In the design of a cross-subsidy system for the electricity sector, it is desired that the system would be self-financed only by contributions from electricity customers [9, 12, 13]. In case the conditions changed from the values used to designed the cross-subsidy mechanism the system would not be able to generate enough resources to be self-financed. Then, the government could provide budget subsidies to finance the deficit in the interest of greater political, economic or social goals. This is the case of the electricity sector in Colombia which has been studied successfully using the model presented in this research [9, 12, 13].Electricity subsidies in Colombia are provided to almost 90% of residential customers, the cross-subsidy system under collects requiring budget subsidies of around 15% for the period from 2005-2007 [9, 12, 13].However, the budget system has increased to almost 60% for the year 2012 [15].Hence the importance of designing optimization models that guide the decision-making process decreasing the risk of making sub-optimal decisions [1-8,12,13]. Then the objective of the present research is to formulate optimization models for determining optimal decision variables for the design of a cross-subsidy system for the electricity sector. The decision-making problem of determining the size of the subsidized and contributing sectors, subsidy and contribution factors, involves the cross-product of these decision variables. This is characterized as a non-linear programming problem. This is also a self-referential problem since it involves determining the electricity

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demand and the price, where electricity demand depends on the price which is a function of the subsidy or contribution factor [8, 12,13]. The solution to this problem in real-life is simplified by input from various stakeholders in the problem. This problem can also be characterized as a bilinear problem [8, 12, 13]. In a bilinear problem, once one variable is specified the problem becomes a linear programming problem in the other variable [8]. This allows solving the problem in a faster way once the size of the subsidized and contributing groups are given or the target levels for susbsidy and contribution factors are given. The author has proposed and algorithm to solve this non-linear problem considering input from different stakeholders involved in the decision makingprocess. The algorithm along with the formulation presented in this paper have been used to propose alternatives to improve the performance of the cross-subsidy system for the Colombian electricity sector [12-13].These alternatives reduce the need for budget subsidies and provide full subsidies to customers in the first income decile[12-13].The most recently available census data (at the moment of this research) for the year 2005 [16] suggests that customers in the first income decile will not be able to pay their electricity bill because it represents almost 100 percent of the average household income[9, 12-13]. Therefore, a limitation of the cross-subsidy sector for the electricity sector in Colombia is that is not able to identify customers that need additional financial support [9, 12-13]. Providing benefits to customers that do not need them, as well as missing the target population are some of the arguments given against subsidies [17-19].Electricity subsidies in British Columbia,Canada [18]and in China [19] have been reported missing the target population providing benefits to higher income consumers. Another argument made against subsidies is based on possible overconsumption due to subsidized prices [17-19]. In cases in which subsidies are used by the government to promote equity, universal access and national development [20-21]basic services are priced low relative to costs, whereas other services are priced high relative to costs to compensate [22-24]. This pricing creates cross-subsidies. Then, subsidized customers are encouraged to consume more, whereas customers from contributing groups reduce their consumption below the efficient level of consumption [17, 20, 25, 26].Statistical comparison of the electricity consumption from subsidized groups found significant differences in the consumption indicating possible overconsumption from subsidized groups in the residential electricity sector in Colombia for the period 2003-2012 [11].

Despite these limitations, subsidies may be needed because of political and equity considerations, as in the electricity sector in Colombia described later in this research. In China, to provide a competitive edge, electricity tariffs are lower than the cost of supply [17] and cheaper than in developed countries [25]. In Brazil, large industrial customers also benefit from lower tariffs to increase their competitiveness [26]. In Colombia, more affluent residential groups contributed a maximum of 60% of their electricity bill towards electricity subsidies at the beginning of the restructuring process in 1994 [27].

In public network enterprises, it is generally believed that cross-subsidies are necessary to comply with their social mission [20, 24]. Subsidies are characteristics of network monopolies developed under public ownership [23]. Subsidies can be used to promote network development; however, once the network is mature, they can be discontinued [23, 28]. Colombia implemented a policy of cross-subsidies after the restructuring of its electricity sector in 1994 [9-13, 29]. Subsidies occur when products or services are priced below their marginal costs. Subsidiesalso occur when the government provides a payment to either producers or consumers directly or indirectly to lower the price of the product or to lower production costs [19, 26, 30, 31].A combination of cross-subsidies and budget subsidies could be implemented in electricity markets in which the government owns and regulates the public network [18, 23]. However, when operation and ownership are separated from regulation, as for instance in the MISO (Midwest Independent System Operator) [7] and PJM (Pennsylvania, New Jersey, and Maryland interconnection) markets in the US, with no political power to access budget subsidies, regulators only have access to cross-subsidies to achieve their social or political goals [23]. Subsidies have been used in the telecommunications industry in France and Canada [23, 24]; postal services in the US [23]; the water industry in Scotland [28]; fossil fuels in China, India, Indonesia, Egypt, Thailand, Venezuela, Saudi Arabia, Iran, Iraq and Mexico [17, 25, 32]; natural gas in Ukraine [32] and China [30]; and in the electricity sector in China,

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Colombia, Brazil, Bolivia, Honduras, Panama, Nicaragua, El Salvador, Mauritania, Jordan, Senegal, Lebanon and Canada [17-19, 32].

The discussion presented here continuous in the following way: section 2 presents the non-linear unconstrained optimization model for minimizing the budget subsidy considering the demand as random; section 3 presents the constrained optimization considering some simplifications in the problem formulation; section 4 describes some applications of the formulation to the electricity sector in Colombia; section 5 concludes the paper.

1. Unconstrained General Problem formulation.

The problem presented in (1) is a Mixed Integer Non-linear Programming (MINLP) problem since it involves the product of the decision variablestrough equations (3) to (4); in addition to any non-linearities proper to the functions representing the price and the electricity demand. Another complexity of this formulation is the self-referential problem [3, 7, 8] involving determining the electricity price, the demand quantity, and the subsistence level. The first term in (3) computes the electricity subsidies for subsidized group *i* when electricity consumption is less or equal than the subsistence level. In this first term of equation (3) the decision variables are the number of users in each subsidized group, subsidy factors, and subsistence level. It is assumed there is a continuous function *f(x)* that determines the price for subsidized groups as a function of the random demand *x*. The second term in (3) computes the cost of any additional more expensive consumption above the subsistence level. In this second term of equation (3) the decision variables are the number of users in each subsidized group that consumes electricity above the subsistence level, subsidy factors for electricity consumption above the subsistence level and subsistence level. It is assumed there is a continuous function that determines the number of electricity users in the subsidized groups that consume electricity above the subsistence level as a function of the electricity price *f(x)*.The first term in (4) computes the electricity subsidies for contributor group *j* when electricity consumption is less or equal than the base level. In this first term of equation (4) the decision variables arenumber of users in each contributor group, contribution factors, and base level. It is assumed there is a continuous function *f(x)* that determines the price for contributing groups as a function of the random demand *x*. The second term in (4) computes the cost of any additional more expensive consumption above the base level for contributing groups. In this second term of equation (4) the decision variables are the number of users in each contributor group that consumes electricity above the base level, contribution factors for electricity consumption above the base level and base level. It is assumed there is a continuous function that determines the number of electricity users in the contributing groups that consume electricity above the base level as a function of the electricity price *f(x)*.

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Min (*Budget Subsidy*)

$$Budget\ Subsidy = Subsidy - Contributions$$

$$Subsidy = \sum_{i} \{u_i \alpha_i \int_0^{x_{sub}} (x_i) f(x_i) dx + \alpha_i' \int_{x_{sub}}^{\infty} (x_i - x_{sub}) u_i'(f(x_i)) f(x_i) dx \}$$

$$Contribution = \sum_{j} \{u_j \beta_j \int_0^{x_{base}} (x_j) f(x_j) dx + \beta_j' \int_{x_{base}}^{\infty} (x_j - x_{base}) u'(f(x_j)) f(x_j) dx \}$$

Notation:

α_i :	Subsidy factor for group *i*
α_i' :	Subsidy factor for group *i*for electricity demand above the subsistence level
β_j :	Contribution factor for group *j*
β_j' :	contribution factor for group *j* for electricity demand above the base level
$f(x$:	electricity price function for group *i*
$f(x$:	electricity price function for contribution group *j*
u_i :	Number of users in subsidized group *i*
u_j :	Number of users in contribution group *j*
$u_i'(f$:	Number of users in subsidized group *i*that consumed electricity above the subsistence level as a function of the electricity price
$u_j'($:	Number of users in contribution group *j* that consumed electricity above the base level as a function of the electricity price
x_{base} :	Base electricity level
x_i :	Random electricity demand group *i*
x_j :	Random electricity demand for contribution group *j*
x_{sub}	Subsistence electricity level

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Decision variables in the problem are: α_i , α_i' , β_j , β_j' , u_i , u_j , x_{base} , x_{sub} .

2. Constrained Problem Formulation

The unconstrained problem formulatedin the previous section is presented here considering some changes in the formulation to make the complex non-linear problem moremanageable. The problem presented in (1) is subject to different constraints as it will be detailed below. The complexities involved in solving (1) to (4) can be reduced by considering information provided by different stakeholders, historical data and laws and regulations governing the electricity sector for which the cross-subsidy system is being designed [12, 13].

The minimization problem is presented below:

$$Min\ Budget\quad Subsidy = Subsidy - Contributions \tag{5}$$

$$P_{S_{i,k}} = CS_{S_{i,k}}(1-\alpha_{S_{i,k}}) \tag{6}$$

$$Subsidy = \sum_{k} \sum_{i=1}^{m} U_{S_{i,k}} Q_{S_{i,k}} \left(CS_{S_{i,k}} - P_{S_{i,k}}\right) = \sum_{k} \sum_{i=1}^{m} U_{S_{i,k}} Q_{S_{i,k}} CS_{S_{i,k}} \alpha_{S_{i,k}} \tag{7}$$

$$P_{C_{j,k}} = CS_{C_{j,k}}(1+\beta_{C_{j,k}}) \tag{8}$$

$$Contributions = \sum_{k} \sum_{j=1}^{n} U_{C_{j,k}} Q_{C_{j,k}} \left(P_{C_{j,k}} - CS_{C_{j,k}}\right) = \sum_{k} \sum_{j=1}^{n} U_{C_{j,k}} Q_{C_{j,k}} CS_{C_{j,k}} \beta_{C_{j,k}} \tag{9}$$

Subject to

$$0 \le LB_{S_{i,k}} \le \alpha_{S_{i,k}} \le UB_{S_{i,k}} \le 1 \tag{10}$$

$$\alpha_{S_{i,k}} \ge \alpha_{S_{i+1,k}} \tag{11}$$

$$0 \le LB_{C_{j,k}} \le \beta_{C_{j,k}} \le UB_{C_{j,k}} \tag{12}$$

$$\beta_{C_{j+1,k}} \ge \beta_{C_{j,k}} \tag{13}$$

Notation:

α	:Subsidy factor for subsidized group *i*in region *k*.
β	:Contribution factor forcontributor group *j* in region *k*.
C	:Contributor group *j* in region *k*.
C	:Cost of supply for subsidized group *i*in region *k*per Kwh.
C	:Cost of supply forcontributor group *j*in region *k*per Kwh.
L B	:Lower bound.
P	:Electricity price for subsidized group *i*in region *k*per Kwh.

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P	:Electricity price for contributor group *j*in region *k*per Kwh.
Q	:Average consumption per customer in subsidized group *i* in region *k*.
Q	:Average consumptionper customer in contributor group *j* in region *k*.
$S_{i,k}$	: Subsidized group *i*in region *k*.
U	: Upper bound
U	: Customers in subsidized group *i* in region *k*.
U	: Customers in contributor group *j* in region *k*.

Equation (5) seeks to minimize the difference between subsidies and contributions. (6) determines the electricity price for subsidized groups as a function of the cost of supply and the subsidy factor. (7) determines the total subsidies considering the number of users in each subsidized group, average electricity demand for each subsidized group, cost of supply and subsidy factor. (8) determines the electricity price for contributing groups as a function of the cost of supply and the contribution factor. (9) determines the total contributions considering the number of users in each contributing group, average electricity demand for each contributing group, cost of supply and contribution factor. (10) gives lower bounds and upper bounds for the subsidy factors. (11) guarantees that the subsidy factor received by a group *i* is greater or equal than that of group *i+1*.(12) gives lower bounds and upper bounds for the contributing factors. (13) guarantees that the contribution factor given by group *j+1* is greater or equal than that of group *j*.

It is worth mentioning that the proposed model can be applied to other public services to design a cross-subsidy mechanism for a system consisting of *m* subsidized categories and *n* contributing categories having a different cost of supply.

3. Applications to the Colombian Electricity Sector.

The constrained optimization model presented in this paper has been used effectively to study the cross-subsidy system in Colombia [12,13]. The model has been used to propose alternatives that do not require budget subsidies from the government. These alternatives also provide full subsidies to low-income customers [12, 13]. The electric sector in Colombia has been considered of academic interest [29] due to the positive results experienced after its deregulation in 1994 related to the quality of service, openness and market and regulatory design. The energy crisis of 1992 motivated the restructuring of the electricity sector in Colombia. During this year hydrological generation capacity was reduced due to an extremely dry season resulting in a long period of load rationing to prevent blackouts. This crisis also had political consequences, transforming politicians and energy planners into risk avoiders favoring over capacity [29, 31]. As a result of the restructuring process in 1994 [33, 34], Colombia implemented a policy of cross-subsidies to promote national development,universal access and social equity.The cross-subsidy system under-collects and requires budget subsidies from the Colombian government of almost 15 percent of the total subsidy amount. However, the budget subsidy was nearly 60 percent for the year 2012 [15]. Then, it is important to monitor the behavior of the system topropose alternatives to improve its performance[9-13].

Unlike unbundled deregulated markets in the US, the Colombian electric system is partially unbundled [29]. Companies are allowed to participate in generation and distribution provided they act independently and do not

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discriminate against other companies [29]. There is also mixed ownership of electricity assets between the government and private sectors. This mixed ownership allows Colombia to implement a combination of cross-subsidies and budget subsidies.The system is financed by contributions from higher income residential customers, industrial and commercial sectors. The government provides budget subsidies to finance any deficit. Electricity in Colombia was provided at a subsidy to 95 percent of residential customers [9-13].

Residential tariffs for electricity in Colombia should be set according to the same residential classification employed in the provision of residential public water service outlined in CREG resolution 012-93 [35]. This system is based on a residential classification of homes to identify the target population in neighborhoods for the purpose of tariff assignment [36]. Based on the residential classification of homes, there are six residential groups from 1 to 6 in increasing order of financial wealth. Groups 1 to 3 are considered low-income groups and are the beneficiaries of the subsidies. Group 4 is considered neither a contributor nor a subsidized sector; it should pay solely for the cost of the service. Groups 5 and 6 are considered higher income groups. These groups contribute to the subsidies in addition to the contributions made by the industrial and commercial sectors.Residential electricity tariffs are defined in resolutions CREG 80-95 [37], CREG 09-96[38] and CREG 78-97 [39], whereas non-residential electricity tariffs are defined in resolution CREG 79-97 [40].

Based on the rules for the sector a simplified general expression to compute tariffs is provided below [9, 11-13]:

$$T(t)_{ijk} = (1+\rho_{ik}(t))\ C_{jk}(t) \tag{14}$$

Where:

$T(t)_{ijk}$: tariff for customer type *i* at voltage level *j* provided by company *k* at time *t*.

$\rho_{ik}(t)$: subsidy or contribution factor for customer type *i*at time *t* provided by company *k*.

$C_{jk}(t)$: cost of supply at voltage level *j* provided by company *k* at time *t*.

The above equation has similarities with (6)and (8) presented in the previous section. It is important to notice that since the studies conducted as part of this research are macro-level studies some simplifications are done to facilitate problem-solving, as well as to compensate for the lack of consistent data. However, given access to enough data the model presented in the previous section could consider additional details such as the cost of supply at different voltage levels per company in (14).

The justification to propose alternative allocation methods for cross-subsidies in Colombia is that the current allocation method does not correlate with the household income [36, 41]. This causes some unfair and inefficient allocation of electricity subsidies [9, 11-13]. Although there are provisions to promote equity in the context of social responsibility in the restructuring of the electric sector in Colombia, there are still around one million users for which electricity bill represents almost 90 % of their income [9]. Then, for these customers, the subsidy system is not providing enough to help them.

According to the available data at the moment of this research average electricity bill for customers in the first income decile represents almost 90% of the household income [9, 12, 16, 42]. Then, the proposed alternatives using the models presented in this research considered improving the current allocation system by giving full electricity subsidies to low-income customers. Alternatives are based on the current allocation system considering six residential groups and on a new allocation system considering the distribution of household income in deciles [9, 12, 13].In order for any of the proposed alternatives to be implemented successfully some policy and regulatory changes are needed to increase subsidy and contribution factors and to redefined contributing groups.

Alternatives that are based on the current allocation system considering six residential groups are easier to implement since they required fewer changes in policies. However, alternatives based on the household income required not only policy and regulatory changes before a possible implementation but the design of a system that registers and classifies customers according to household income and then assigns corresponding electricity tariffs. In general terms, the success of the proposed alternatives [9, 12, 13] using the models presented in this research is based on increasing the number of contributors as well as the contributing factors. Alternatives are financed only by contributions from residential customers alone. This avoids impacting commercial and industrial customers with significant price increases which could most likely cause a reduction in their electricity demand. In India, using an increase in electricity prices for industrial customers to provide for residential and agricultural sectors as a financial mechanism was determined to be unsustainable because price increases caused reductions in industrial demand; subsequently, the system failed to collect sufficient money to pay for subsidies [20].

CONCLUSION

The optimization problem of designing a cross-subsidy system for the electricity sector is defined as a Mixed Integer Non-linear Programming (MINLP) problem since it involves the product of the decision variables [3, 7, 8, 12, 13]in the objective function;in addition to any non-linearities proper to the functions representing the price and the electricity demand. Another complexity of this formulation is the self-referential problem [3, 7, 8, 12, 13] involving determining the electricity price, the demand quantity, and the subsistence level. It is important to remember that although electricity consumption is a random variable with daily, seasonal and regional fluctuations, in macro-level optimization models applied to the electricity sector [1-13] some simplifications are made to facilitate problem-solving. These simplifications could include considering the demand as deterministic and the electricity price as given. In the design of a cross-subsidy system for the electricity sector, it is desired that the system would be self-financed only by contributions from electricity customers [12, 13]. In case the conditions changed from the values used to designed the cross-subsidy mechanism the system would not be able to generate enough resources to be self-financed. Then, the government could provide budget subsidies to finance the deficit in the interest of greater political, economic or social goals.

However, subsidies are disliked by some because they could cause an inefficient allocation of resources due to overconsumption and the risk of missing the target population. In spite of that, subsidies could be needed to achieve social goals and to promote equity. Then, there is a need to develop mathematical models and other mechanisms [9-13] to study the behavior of the subsidy system. This research presents two optimization models to minimize the budget subsidy. The constrained model presented in this research has been applied to study the cross-subsidy sector in Colombia [9, 12, 13]. It is important to mention that the proposed model could be used to study any other cross-subsidy system after making any necessary adjustments. Electricity in Colombia is provided at a subsidy to 90% of residential customers. The cross-subsidy system under collects requiring budget subsidies from the government. The proposed optimization models presented in this research have been used to identify alternatives that do not require budget subsidies from the government [9, 12, 13]. These alternatives also provide full subsidies to customers in the first income decile since their electricity bill could represent 90% of the household income [9, 12, 13, 16, 42].Then, there is scope for optimization models to be used in the design of a cross-subsidy system to reduce the inefficient allocation of resources due to overconsumption and missing the target population. Nevertheless, additional research studies are needed to test the applicability of these models in more real-life cases to promote their widespread usage in the design of energy policies.

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