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Evaluating the impact of demand uncertainty on cross-subsidies and budget subsidies in the electricity sector in Colombia

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Abstract: Policy and planning decisions should include uncertainty in electricity demand to avoid the risk of suboptimal decisions that result in inefficient resource allocation. Uncertainty in electricity demand can be represented by using random demand scenarios. This research evaluates the impact of uncertainty in electricity demand in budget subsidies by using an optimization model in which demand is considered a random variable. This model is applied to a test case based on the electricity sector in Colombia. Colombia provides subsidies to 95% of residential customers during the research period. However, the cross-subsidy system in Colombia requires budget subsidies from the government of 15percent. Results over one hundred random demand values for each residential group at two different levels of demand variabilityindicate that it is very unlikely that the Colombian system can generate enough funds to provide subsidies to 90% of the residential customer without the need for budget subsidies. Results indicate that even small variations in electricity demand upset the balance of subsidies and contributions. Joint multidisciplinary efforts are needed to address this issue using the method proposed in this research.

Keywords:electricity tariffs; cross-subsidy; budget subsidy; demand uncertainty; deregulated electricity sector;Colombia.

1. Introduction

Energy policies failing to include uncertainty in electricity demand most likely result in suboptimal decisions in the allocation of resources. Electricity subsidies already face strong opposition due to inefficient allocation of resources and the likelihood of providing benefits to customers that do not need them. Therefore, the need for additional research studies focused on providing mathematical models for decision making applied to the electricity sector [1-14]. Variations in electricity demand affect the balance of subsidies and contributions in a cross-subsidy system like the one implemented in Colombia, described later in this paper [9-14]. Electricity demand varies depending on several aspects such as time of the day, day of the week and season [1-9]. However, macro-level optimization models applied to the electricity sector [1-14] often include simplifications to facilitate problem-solving. These simplifications could include considering electricity demand as deterministic and the electricity price as given. It is common practice to consider demand as deterministic usually set at a peak level since this generally represents the worst-case scenario [1-9]. Another alternative is to consider average values for electricity demand and prices [10-14]. Stochastic random demand can also be considered in the analysis by using demand scenarios generated randomly [7] or by representative future conditions [15].Fluctuations in electricity demand due to overconsumption from subsidized groups affect the balance of the system from the design conditions requiring additional funds to cover the deficit. In this case, the government could provide budget subsidies to finance the deficit to achieve social or political goals. This is the case of the electricity sector in Colombia which is used in this research to evaluate the impact of uncertainty in electricity demand over budget subsidies. 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 [10, 12-14]. However, the budget system has increased to almost 60% for the year 2012 [13]. Hence the importance of designing optimization models that guide the decision-making process decreasing the risk of making sub-optimal decisions [1-9, 14]. Then the objective of the present research is to evaluate the impact of demand uncertainty over budget subsidies. The research presented here extends the research presented in [9, 14] by considering demand fluctuations at two levels. This optimization problem involves the cross-product of decision variables [9, 14]. This problem is characterized as a non-linear programming problem [9]. This is a self-referential problem involving determining the electricity demand and the price, where electricity demand depends on the price which is a function of the subsidy and contribution factor [8, 9,12-14]. This problem is also a bilinear problem [8, 9, 12-14]. In a bilinear problem, once one variable is specified the problem becomes a linear programming problem in the other variable [8]. This simplifies the problem once the size of the subsidized and contributing groups are given or the target levels for subsidy and contribution factors are given [9]. The research presented here uses the model formulated in [14] over a set of 100 demand scenarios generated randomly from normal distributions considering demand variability at two levels. The objective of this research is to evaluate the impact of demand uncertainty at two different levels over budget subsidies using a test case based on the electricity sector in Colombia.

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 [10, 12-13]. Therefore, the cross-subsidy sector for the electricity sector in Colombia has a limitation in its capacity to provide additional support for customers in extreme poverty [10, 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]. For instance, 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 electricity consumption indicating possible overconsumption from subsidized groups in the residential electricity sector in Colombia for the period 2003-2012 [11].

Electricity demand curves for subsidized (S) and contributing (C) groups are presented in Figure 1. Consider the price for the subsidized group (P_s) isset below the cost of supply (CS), whereas the price for the contributors (P_c) is set above the cost of supply. This cross-subsidy pricing causes an increase in consumption in the subsidized sector from Q_S(CS) to Q_s and consumption in the subsidizing sector to decrease from Q_C(CS) to Q_C. The balance of subsidies and contributions requires $Q_s * (CS- P_s)$ to be equal to $Q_C * (P_c -CS)$ [20]. The uncertainty in electricity demand is represented in Figure 1 by using bell shape curves with means $\mu_s=Q_s$ and $\mu_c=Q_C$. The electricity demand is a random variable that fluctuates depending on the time of the day, day of the week and season. At any time*t*, the realization of the demand is random according to its probability distribution. Its realized value could fall on either side of the mean demand μ. This variability affects the balance between subsidies and contributions. Therefore, the amount of budget subsidies from the government would change. The research proposed here seeks to make a contribution by presenting a method to analyze the impact of demand uncertainty based on the design parameters defined by energy policymakers, politicians, and other relevant stakeholders.

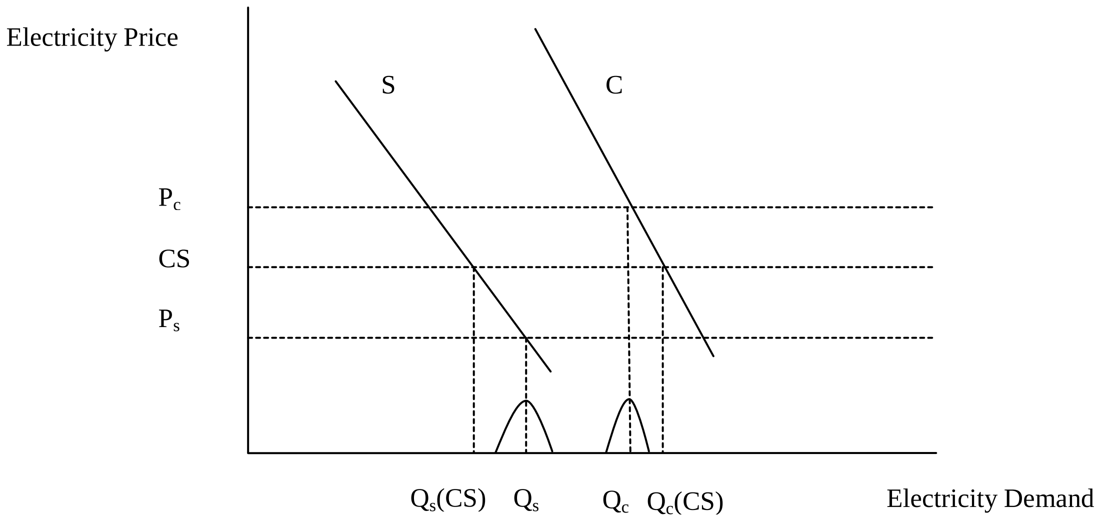

Figure 1. Demand curves for Subsidized and contributor groups.

In public network enterprises,cross-subsidies are considered necessary to comply with their social mission [20, 24]. Chinaprovides a competitive edge to electricity customers by lowering electricity prices below the cost of supply [17] resulting in electricity prices cheaper than in developed countries [25]. Brazil provides a similar benefit to large industrial customers by means of lower electricity prices to increase its competitiveness [26]. In Colombia, higher income residential groups contributed a maximum of 60% of their electricity bill towards electricity subsidies at the beginning of the restructuring process in 1994 [27]. Subsidies can be used to promote network development; however, once the network is mature, they can be discontinued [23, 28]. Subsidies are characteristics of network monopolies developed under public ownership [23]. Colombia implemented a cross-subsidy system after the restructuring of its electricity sector in 1994 [10-13, 29]. Pricing products or services below their marginal costs or providing direct payments to producers or consumers originates subsidies [19, 26, 30, 31]. In electricity markets in which the government owns and regulates the public network a combination of cross-subsidies and budget subsidies could be implemented to achieve social or political goals[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, Colombia, Brazil, Bolivia, Honduras, Panama, Nicaragua, El Salvador, Mauritania, Jordan, Senegal, Lebanon and Canada [17-19, 32].

2. Materials and Methods.

This research extends the work presented in [9, 14] by evaluating the impact of demand uncertainty at two different levels over budget subsidies, electricity prices and subsidy and contribution factors. Electricity demand is considered as a random variable. Demand scenarios are then used to represent uncertainty in electricity demand. The optimization problem of designing a cross-subsidy systemrequires determining subsidy and contribution factors as well as the size of the subsidized and contributing groups. This problem is a Mixed Integer Non-linear Programming (MINLP) problem[9, 14] since it involves the product of the decision variables in the objective function. This optimization problem is also a self-referential problem [3, 7-9, 14] since the electricity price, the demand quantity, the subsistence and base level depend on each other. Additional complexities in the problemare due to any non-linearities proper to the functions representing the price and the electricity demand. In macro-level decision making some simplifications are made to facilitate problem-solving. These simplifications include considering the problem as deterministic ignoring randomness in electricity demand and prices. Another simplification consists of including variability in prices and demand by using representative scenarios [7, 14]. Demand scenarios are used by the Midwest Independent System Operator (MISO) in the capacity validation study [7, 14] to determine expansion plans for three possible future demand scenarios [14]. The decision makers selected all of the transmission lines common to all three scenarios for implementation. In the cases presented here, the optimization model finds optimal subsidy and contribution factors for each scenario minimizing the average budget subsidy over all scenarios [7, 14].

The model presented in [14]is applied to two sets of 100 demand values generated randomly from normal distributions considering two cases of demand variability represented as standard deviation at 5 percent or 10 percent of the mean demand. In cases in which historical values are available, the variance can be estimated from the data. Demand values are generated using the function random variate from the normal distribution in Mathematica version 10, setting the seed as 19. The mean values are obtained from average electricity consumption per subscriber, presented in the next section. The standard deviation is set at 5 percent or 10 percent of corresponding mean values for each customer group. The cost of supply for residential customers is set as the average electricity price for customers in group 4. This value corresponds to 0.17 $/Kwh. The average cost of supply for industrial, commercial and other sectors is estimated from equation (5) using the average values in tables 2 and 6. These values correspond to 0.0912560, 0.1209873 and 0.1278521 $/Kwh, respectively.

2.1. Characteristics of the Cross-Subsidy System in Colombia.

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]. All of these issues resulted in a restructuring process in 1994 [33, 34], using cross-subsidies to promote national development, universal access, and social equity. The cross-subsidy system in Colombia under-collects and requires budget subsidies from the government of almost 15 percent of the total subsidy amount. However, the budget subsidy was nearly 60 percent for the year 2012 [14]. Then, it is important to monitor the behavior of the system to propose alternatives to improve its performance [9-13].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 customers 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 in (11) [9, 11-13].This equation has similarities with (3) and (5) presented in the previous section.

$$T(t)_{ijk} = (1+\rho_{ik}(t))\ C_{jk}(t) \tag{11}$$

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*.

According to Figure 2 residential group 1 represents 24 percent of residential customers; whereas groups 2, 3 and 4 represent 40 percent, 25 percent, and 6 percent respectively. Approximately 95 percent of residential customers received subsidies from the system during the three-year study period. Values in table 1 indicate that subsidized groups grow faster than residential contributors. This growth will most likely upset the balance between subsidies and contributions requiring additional budget subsidies from the government.

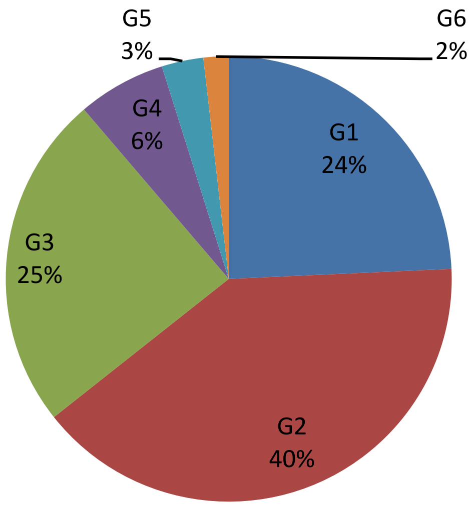

Figure 2. Average distribution of residential customers.

Year	2005	2006	2007
G1	1688190	2036695	2319139
G2	3158880	3269392	3543892
G3	1978779	1953378	2144513
G4	497920	500839	593237
TotalSubsidized	7323769	7760304	8600781
G5	235417	244844	273781
G6	135190	142652	175451
Total Residential	7694376	8147800	9050013
Industrial	75967	71370	77848
Commercial	634042	624852	693940
Government	56249	50352	48943
Others	27111	27112	29906

Table 1. Subscribers per group per year.

Average electricity prices for subsidized groups are lower for group 1 and an increase for the other groups, Table 2. Electricity prices for contributing residential sectors during two years are greater for customer type 5 than for customer type 6. The opposite behavior is expected according to equity principles include in the design of the system. Initial contributions values for contributing groups were designed considering this, such that $\rho_{5k} < \rho_{6k}$[37]. But after the year 2000 all, contribution factors were set to be lower or equal to a limiting value of 20 percent [40]. This behavior in the prices is also found by the author in a separate study conducted for the electricity sector in Colombia for the majority of the years from 2003 until 2012 [11].

Year	G1	G2	G3	G4	G5	G6	Industrial	Commercial	Others
2005	0.12	0.14	0.18	0.19	0.22	0.21	0.14	0.18	0.16
2006	0.11	0.13	0.16	0.17	0.20	0.19	0.13	0.16	0.15
2007	0.10	0.12	0.14	0.16	0.17	0.17	0.08	0.11	0.09
Average	0.11	0.13	0.16	0.17	0.20	0.19	0.11	0.15	0.13

Table 2 Average electricity price $/Kwh (Constant US$ for 2007)

Year	G1	G2	G3	G4	G5	G6	Industrial	Commercial	Government	Others
2005	168.11	141.92	174.16	219.74	286.48	437.24	13926.52	886.32	2136.70	4995.69
2006	148.11	138.34	171.81	217.15	273.56	417.93	15094.47	923.04	2216.42	4724.65
2007	124.83	134.58	167.36	206.48	255.91	360.79	19379.03	1101.82	3949.80	6411.87
Average	147.02	138.28	171.11	214.45	271.98	405.32	16133.34	970.39	2767.64	5377.40

Table 3. Average electricity consumption per subscriber (kWh per month)

Average consumption (table 3) for all subsidized sectors is below the subsistence level of 200 kWh per month [12, 37]. However, during two years average consumption for group 1 is higher than that of group 2 [11]. This may indicate overconsumption due to low electricity prices. Average electricity consumption in residential sectors increases as one moves up in the social groups. Average consumption for residential customers in group 6 is more than twice the consumption for group 1. Industrial and commercial demands are also increased during the study period at a higher rate than residential consumption. This is positive in terms of collecting funds for subsidies.

Year	G1	G2	G3	G4	G5	G6	Industrial	Commercial	Government	Others
2005	22.42	19.35	23.09	28.50	35.57	53.57	1065.61	86.30	240.03	537.58
2006	19.54	18.27	21.86	26.99	32.48	49.12	1122.67	85.29	238.07	484.12
2007	15.67	16.54	19.75	23.91	28.16	39.48	937.23	72.26	226.64	421.78
Average	19.21	18.05	21.57	26.47	32.07	47.39	1041.84	81.28	234.91	481.16

Table 4. Average electricity bill per subscriber per month in USD.

Table 4 presents the average electricity bill per subscriber per month in constant USD for 2007. There is no much difference in the average bill between groups 1 and 2 despite the subsidy level each group receive is different, as reported in table 5 [11]. Group 1 receives on average a subsidy of 41 percent; whereas group 2 receives a subsidy of 29 percent. Industrial bill is the highest making them the more important contributors. This sector has the highest consumption of all (Table 3) distributed among only approximately 75.000 clients (Table 1). In countries such as China [25] and Brazil [26], industrial customers receive electricity subsidies to make products from the sector more competitive. Contributions from the commercial sector (table 6) are approximately 24 percent. Contribution factors for industrial and commercial sectors are exceeding limiting factors most likely due to additional income in these sectors due to other service fees.

Year	G1	G2	G3
2005	0.4081	0.2948	0.0973
2006	0.3954	0.2953	0.0932
2007	0.4311	0.2795	0.0855
Average	0.4116	0.2899	0.0920

Table 5. Subsidy factor per group.

Year	G5	G6	Industrial	Commercial	Others
2005	0.1814	0.1768	0.2034	0.2308	0.0185
2006	0.1813	0.1750	0.2011	0.2347	0.0156
2007	0.1846	0.1763	0.2117	0.2539	0.0163
Average	0.1825	0.1761	0.2054	0.2398	0.0168

Table 6. Contribution factor per group.

Table 7 reports the percentage of total subsidy covered by the budget subsidy. The cross-subsidy system given the actual subsidy and contribution factors reported in the two tables above fails to collect enough funds to avoid the need for budget subsidy. The budget subsidy from the government represents on average approximately 15 percent of the total subsidy amount after discounting all contributions. The system on its own given the current contribution levels is not able to provide enough to give subsidies to 95 percent of residential customers at the actual subsidy levels reported in table 5.

Year	percent Budget Subsidy
2005	15.14
2006	15.71
2007	13.00

Table 7. Percentage Budget Subsidy.

3. Results

Table 8 reports the optimal values obtained from the model presented in this research considering two cases of demand variability. There is not much difference between the two cases in terms of the average budget subsidy needed to cover the deficit from the contributions. The average budget subsidy for each sample case is almost 15 percent. This is similar to the average budget subsidy reported for the study period in table 7. However, when the standard deviation represents 10 percent of the mean demand, the maximum budget subsidy increases by almost 4 percent compared to the case when the standard deviation represents 5 percent of the mean demand. Then at 10 percent demand variability, there is a 98% probability of requiring a budget subsidy. This probability is almost one for the two cases presented here, which consider conservative variations in electricity demand. The associated probability of generating enough funds to cover consumption from customers in the first income decile is zero.It is assumed that customers in group 1 represent customers in the first income decile [10-13]. Figure 2 presents budget subsidy (percent) for each demand scenario at a 10 percent standard deviation. Notice that there is no observable pattern in the values and that the budget subsidy could change considerably at values of demand that are not too far from each other. A curve representing a normal distribution has been superimposed on these data points to illustrate the demand variability represented in Figure 1. Figure 2 shows that even small changes in total demand can affect the balance between subsidy and contributions requiring budget subsidies. Results from this case seem to indicate that the important factor in the variation of the amount of budget subsidy is the distribution of the changes in the demand among all the groups. A limitation of the analysis presented here is the assumption that variation in electricity demand among groups is homogenous.Another important underlying assumption is that electricity demand is price-inelastic. These limitations can be overcome with access to realdatato estimate demand variability and elasticity per group in each region. However, access to this data is currently not available.

	10 percentstandard deviation demand	5 percentstandard deviation demand
Average Budget subsidy	14.50 percent	14.87 percent
	0 – 28.89 percent	7.45-24.50 percent
P(Requiring Budget Subsidy)	98 percent	1
P(Covering 1st subsidized group)	0	0
α_{S_1}	0.4	0.4
α_{S_2}	0.3	0.3
α_{S_3}	0.08	0.08
$Range \ \ \beta_{c_5}$	0.15-0.20	0.2
β_{c_6}	0.2	0.2
$\beta_{c_{Industrial}}$	0.2	0.2
$\beta_{c_{Commercial}}$	0.2	0.2
$\beta_{c_{Others}}$	0.05	0.05
P_{S_1}	0.102	0.102
P_{S_2}	0.119	0.119
P_{S_3}	0.1564	0.1564
$Range \ \ P_{c_5}$	0.1955-0.204	0.204
P_{c_6}	0.204	0.204
$P_{c_{Industrial}}$	0.1095	0.1095
$P_{c_{Commercial}}$	0.1452	0.1452
$P_{c_{Others}}$	0.1342	0.1342
Range Demand	19124.74- 28844.16 MWh	21714.66-25910.62 Mwh

Table 8. Optimal solution range considering 100 samples at 5 percent and 10 percent demand variance.

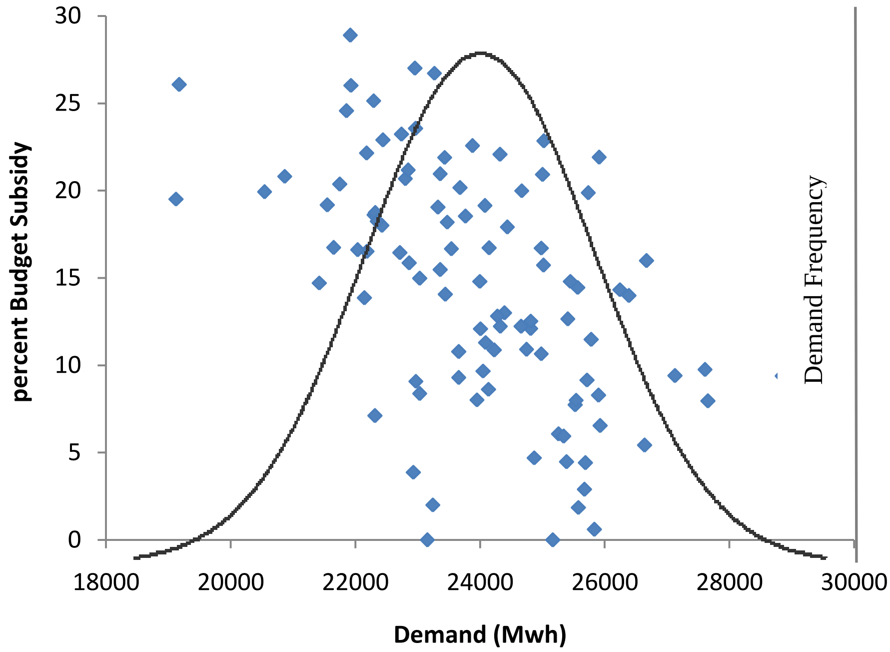

Figure 2. Budget subsidy (percent) for each demand scenario at 10 percentstandard deviation.

In terms of the range of optimal values for subsidy and contribution factors presented in table 8, the subsidy factors for all of the groups in all of the cases are set at the lower bounds, whereas the contributing factors are set at the upper bounds for all groups in all cases except one in which the contribution factor for group 5 is set at the lower bound. The philosophy behind the solution is to give the minimum subsidy and collect the maximum contribution. This seems to be in accordance with the properties of linear programming since this bilinear problem reduces to a linear program once the size of the subsidized and contributing sectors are given. Values for price range provide limited information in this case because the bounds imposed on the subsidy and contribution factors give no flexibility in terms of setting different prices for each scenario. In the 10 percent standard deviation demand case, the prices for customers in group 5 vary in one sample from 0.1955 to 0.204 $/MWh. The demand varies from 19124.74 up to 28844.16 MWh in the case in which the standard deviation of the demand is considered to be 10 percent of the mean demand. The demand varies from 21714.66 up to 25910.62 MWh in the case in which the standard deviation of the demand is considered to be 5 percent of the mean demand.

4. Discussion

Energy policy and planning decisions need to include uncertainty in electricity demand to avoid the risk of suboptimal decisions that result in inefficient resource allocation. Efficient self-sustained cross subsidy policies require a balance of subsidies and contributions. Real-time variations in electricity demand affect the balance between subsidies and contributions. In cases in which subsidies are greater than contributions, additional funds are provided by means of budget subsidies. After the restructuring of its electricity sector in 1994, 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 [14], which highlights the importance of designing an efficient cross-subsidy system that considers demand uncertainty.

This research evaluates the effect of demand uncertainty over the minimum average budget subsidy for the Colombian electricity system over a set of demand scenarios considering demand variability at two levels.The optimal results over a set of 100 random demand scenarios at two levels of demand variation given the prevailing bounds on subsidy and contribution factors indicate that the probability of requiring a budget subsidy is almost one. The average budget subsidy for these samples is almost 15 percent. This value is similar to the actual average budget subsidy for the study period. The maximum budget subsidy for the test cases is 29 percent. It can be inferred from the results that the cross-subsidy system for the electricity sector in Colombiacan not provide subsidies to 95 percent of its residential customers without requiring budget subsidies from the government. The method presented in this research shows that using the model formulated in [14] uncertainty in electricity demand can be included in energy policy and planning decisions. However, a joint multidisciplinary effort is needed to reach consensus regarding the bounds on the parameters to be used in the model in order to minimize budget subsidies from the government while achieving social and equity goals.

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