A Bi-level Stackelberg Game Model for Multi-Energy Retail Package Optimization

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Optimization variables

$Q_{i,k}^{\mathrm{B}}$	Electricity purchased from bilateral contract *k* of retailer *i*.
$Q_{t,i,\omega}^{\mathrm{Spot}}$	Electricity purchased from spot market of retailer *i* at period *t* in scenario ω.
$G_{i,k}^{\mathrm{Re,B}}$	Natural-gas purchased from bilateral contract *k* of retailer *i*.
$G_{t,j,k,n}^{\mathrm{User,B}}$	Natural-gas purchased by type *n* end-user *j* from bilateral contract *k* at period *t*.
$Q_{t,i,j,n}^{\mathrm{User}}$ / $G_{t,i,j,n}^{\mathrm{User}}$	Electricity/natural-gas purchased by type *n* end-user *j* from retailer *i* at period *t*.
$p_{\mathrm{k},n}^{\mathrm{E},1}$ / $p_{\mathrm{f},n}^{\mathrm{E},1}$ / $p_{\mathrm{v},n}^{\mathrm{E},1}$	The electricity price of type *n* end-user at peak/flat/valley period in package 1.
$p_{t,n}^{\mathrm{E},1}$ / $p_{t,n}^{\mathrm{G},1}$	The electricity/natural-gas price of type *n* end-user at period *t* in package 1.
$p_{\mathrm{day},n}^{\mathrm{E},2}$ / $p_{\mathrm{night},n}^{\mathrm{E},2}$	The electricity price of type *n* end-user at day/night period in package 2.
$p_{t,n}^{\mathrm{E},2}$	The electricity price of type *n* end-user at period *t* in package 2.
$p_{\mathrm{ba},n}^{\mathrm{E},3}$ / $p_{\mathrm{re},n}^{\mathrm{E},3}$ / $p_{\mathrm{pe},n}^{\mathrm{E},3}$	The basic/reward/penalty electricity price of type *n* end-user in package 3.
$p_{\mathrm{1st},n}^{\mathrm{E},4}$ / $p_{\mathrm{2nd},n}^{\mathrm{E},4}$ / $p_{\mathrm{3rd},n}^{\mathrm{E},4}$	The electricity price of type *n* end-user at first/second/third level in package 4.
$p_{\mathrm{ba},n}^{\mathrm{G},4}$ / $p_{\mathrm{re},n}^{\mathrm{G},4}$ / $p_{\mathrm{pe},n}^{\mathrm{G},4}$	The basic/reward/penalty natural-gas price of type *n* end-user in package 4.
$p_{n}^{\mathrm{E},5}$ / $p_{n}^{\mathrm{G},5}$	The electricity/natural-gas price of type *n* end-user in package 5.

Other variables

$C_{i,\omega}^{\mathrm{E,Re}}$	The cost of purchasing electricity for retailer *i* in scenario ω.
$C_{i}^{\mathrm{G,Re}}$	The cost of purchasing natural-gas for retailer *i*.
$B_{i,m}$	The income of retailer *i* by package *m*.
$C_{i,j,m}^{\mathrm{E,User}}$ / $C_{i,j,m}^{\mathrm{G,User}}$	The cost of purchasing electricity/ natural-gas from retailer *i* by package *m* for end-user *j*.
$C_{j}^{\mathrm{G,User,B}}$	The cost of purchasing natural-gas by bilateral contracts for end-user *j*.
$Q_{i,j,n}^{\mathrm{User,Ex,2}}$	The excess quantity of night-time electricity demand of type *n* end-user *j* in package 2 provided by retailer *i*.
$\varepsilon_{i,j,n}$	The peak-valley excess coefficient of type *n* end-user *j* in package 3 provided by retailer *i*.
$Q_{i,j,n}^{\mathrm{Month}}$ / $G_{i,j,n}^{\mathrm{Month}}$	Monthly electricity/natural-gas purchased of type *n* end-user *j* from retailer *i*.
$Q_{t,j,n}^{\mathrm{Total}}$ / $G_{t,j,n}^{\mathrm{Total}}$	The total electricity/natural-gas demand of type *n* end-user *j* at period *t*.
B_{i}^{Re} / PR_{i}^{Re}	The income/profit of retailer *i*.
R_{i}^{VaR} / R_{i}^{CVaR}	The CVaR/VaR value of retailer *i*.
$C_{i,\omega}^{\mathrm{R}}$ / $F_i(y,\omega)$	The cost/risk loss function of retailer *i* in scenario ω.
δ_i/$x_{i,\omega}$	Auxiliary variables of retailer *i* for measuring risk by CVaR.
$S_{j}^{\mathrm{E,Com}}$ / $S_{j}^{\mathrm{E,Eco}}$	The electricity comfort /economy satisfaction of end-user *j*.
$S_{j}^{\mathrm{G,Com}}$ / $S_{j}^{\mathrm{G,Eco}}$	The natural-gas comfort /economy satisfaction of end-user *j*.
S_{j}^{Energy}	The overall energy satisfaction of end-user *j*.

$Q_{t,j,n}^{\mathrm{In}} / G_{t,j,n}^{\mathrm{In}}$ The initial electricity/natural-gas demand of type *n* end-user *j* at period *t*.

$C_j^{\mathrm{E,In}} / C_j^{\mathrm{G,In}}$ The initial electricity/natural-gas cost of end-user *j*.

TABLE I*

QUOTATION PARAMETERS

Quotation Parameters	Value
Power generation company 1 ($/kWh)	0.035
Power generation company 2 ($/kWh)	0.026
Natural gas company 1 to retailers ($/m^3)	0.20
Natural gas company 2 to retailers ($/m^3)	0.22
Natural gas company 1 to residential/commercial/ industrial end-users ($/m^3)	0.35/0.45/0.4
Natural gas company 2 to residential/commercial/ industrial end-users ($/m^3)	0.4/0.5/0.45

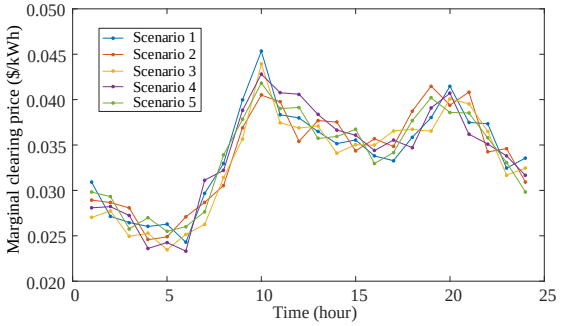

Fig. 1* MCP scenarios in the spot market

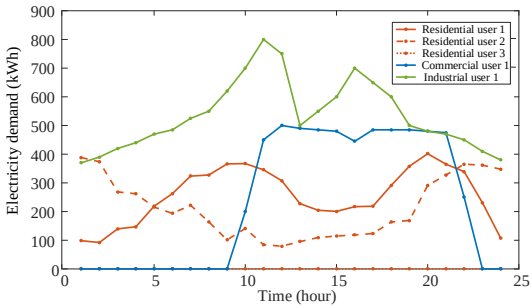

Fig. 2* Initial electricity demand of end-users

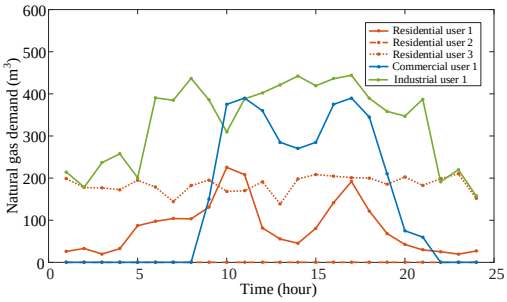

Fig. 3* Initial natural-gas demand of end-users

TABLE II*

PACKAGE PARAMETERS

Package	Parameters	Value
2	Bundled sale proportion	0.5
	Limit value of night-time electricity demand (kWh)	800
3	Limit value of electricity demand at peak period (kWh)	1200
	Limit value of electricity demand at valley period (kWh)	1000
	Boundary value of peak-valley excess coefficient (kWh)	800
4	The first level of electricity demand (kWh)	80000
	The second level of electricity demand (kWh)	100000
	The natural-gas quota value (m^3)	8000

TABLE III*

OTHER PARAMETERS INVOLVED IN SOLVING THE MODEL

Other Parameters	Value
Risk factor weight of each retailer	0.4
The confidence level	0.95
The size of PSO population	30
The number of iterations	101
The acceleration factors in PSO	2
The iteration precision	10^{-3}
Satisfaction weights of end-users for electricity comfort/economy	0.1/0.4