

# Pricing in Integrated Heat and Power Markets – Online Appendix

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## NOMENCLATURE

### Acronyms

IHPD	Integrated heat and power dispatch.
IHPM	Integrated heat and power market.
ISO	Independent system operator.
PM-IHPM	Pricing method for the integrated heat and power market.

### Sets and Indices

$g \in \mathcal{E}$	Electric energy generation units.
$g \in \mathcal{E}^+$	Dispatched electric energy generation units.
$g \in \mathcal{T}$	Thermal energy generation units.
$g \in \mathcal{T}^+$	Dispatched thermal energy generation units.
$i \in \mathcal{D}$	Electricity user.
$i \in \mathcal{D}^+$	Dispatched electricity user.
$j \in \mathcal{Q}$	Heating user.
$j \in \mathcal{Q}^+$	Dispatched heating user.
$l$	Operation bounds for generation units.

### Parameters

$b_i^h$	Value of heating consumption.	[\$/MWh]
$b_i^p$	Value of electric consumption.	[\$/MWh]
$c^{(\cdot)}$	Generation cost coefficients.	
$K_{g,l}^{(\cdot)}$	Coefficients for generation boundaries.	

### Variables

$\gamma^{\text{PM}}$	Heating price after correction.	[\$/MWh]
$\lambda^{\text{PM}}$	Electricity price after correction.	[\$/MWh]
$\Phi_i$	Net electric demand value.	[\$]
$\Pi_g$	Electric generation profit.	[\$]
$\Psi_i$	Net heating demand value.	[\$]
$\Theta_g$	Heating generation profit.	[\$]
$d_i$	Electric demand.	[MWh]
$m_g^h$	Marginal heat generation cost.	[\$/MWh]
$m_g^p$	Marginal electricity generation cost.	[\$/MWh]
$p_g, h_g$	Electricity and heat generation.	[MWh]
$q_j$	Heating demand.	[MWh]
$u_i^{\text{pd}}, u_i^{\text{cd}}$	Electric demand uplift payments and charges.	[\$/MWh]
$u_g^{\text{pg}}, u_g^{\text{cg}}$	Electric generation uplift payments and charges.	[\$/MWh]
$v_j^{\text{pd}}, v_j^{\text{cd}}$	Heating demand uplift payments and charges.	[\$/MWh]
$v_g^{\text{pg}}, v_g^{\text{cg}}$	Heating generation uplift payments and charges.	[\$/MWh]

### Dual variables

$\gamma$	Heating price of the IHPD.	[\$/MWh]
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$\lambda$	Electricity price of the IHPD.	[\$/MWh]
$\mu_{g,l}$	Dual variable related to the operation at the generation boundaries.	[\$]

## APPENDIX A: GENERATION DATA

The coefficients for the generation bounds are presented in Table I. While Table II contains the cost coefficients.

TABLE I  
GENERATION BOUNDARIES' COEFFICIENTS

$l$	Generator 1			Generator 2		
	$K_{g,l}^p$	$K_{g,l}^h$	$K_{g,l}^0$	$K_{g,l}^p$	$K_{g,l}^h$	$K_{g,l}^0$
1	-1.00	-0.05	-44.00	-1.00	0.00	35.00
2	-1.00	1.16	46.88	-1.00	2.20	9.00
3	1.00	0.15	130.70	1.00	0.33	105.00
4	1.00	0.00	125.80	0.00	-1.00	0.00
5	0.00	-1.00	0.00	–	–	–

TABLE II  
GENERATION COST COEFFICIENTS

	$c_{2,g}^p$	$c_{1,g}^p$	$c_{2,g}^h$	$c_{1,g}^h$	$c_g^{\text{hp}}$	$c_g^0$
Generator 1	0.0435	36	0.027	0.6	0.011	12.5
Generator 2	0.072	20	0.02	2.34	0.04	15.65

## APPENDIX B: SUMMER DISPATCH RESULTS

The results of the integrated heat and power dispatch for the Summer scenario are given in Table III. Table IV presents the results of the cost allocation in the Summer scenario.

TABLE III  
SUMMER IHPD RESULTS

$SW = \$ 499.03 \quad \lambda = 30 \text{ \$/MWh} \quad \gamma = 4.27 \text{ \$/MWh}$				
User	Type	Dispatched demand [MWh]	Electric surplus [\\$]	Heat surplus [\\$]
1	$\mathcal{D}$	100	500	–
2	$\mathcal{D}$	9.71	0	–
3	$\mathcal{Q}$	60	–	343.8
4	$\mathcal{Q}$	10	–	107.3
Generator	Dispatched electricity [MWh]	Dispatched heat [MWh]	Electric surplus [\\$]	Heat surplus [\\$]
1	40.27	70	-413.57	-38.5
2	69.44	0	0	0

TABLE IV  
SUMMER CA-IHPD RESULTS

$SW = \$ 498.72 \quad \lambda^{PM} = 35 \$/MWh \quad \gamma^{PM} = 4.82 \$/MWh$						
User	$u^{pd}$ [\$/MWh]	$u^{cd}$ [\$/MWh]	$v^{pd}$ [\$/MWh]	$v^{cd}$ [\$/MWh]	Electric surplus [\$]	Heat surplus [\$]
1	0	0	–	–	0	–
2	5	0	–	–	0	–
3	–	–	0	0	–	310.62
4	–	–	0	0	–	101.77
Generator	$u^{pg}$ [\$/MWh]	$u^{cg}$ [\$/MWh]	$v^{pg}$ [\$/MWh]	$v^{cg}$ [\$/MWh]	Electric surplus [\$]	Heat surplus [\$]
1	5.27	0	0	0	0	0
2	0	3.76	0	0	86.33	0

#### APPENDIX C: WINTER DISPATCH RESULTS

Table V shows the dispatch results for the Winter case. The electricity cost-allocation results are given in Table VI.

TABLE V  
WINTER IHPD RESULTS

$SW = \$ 5\,584.79 \quad \lambda = 10.95 \$/MWh \quad \gamma = 50 \$/MWh$				
User	Type	Dispatched demand [MWh]	Electric surplus [\$]	Heat surplus [\$]
1	$\mathcal{D}$	100	2 405	–
2	$\mathcal{D}$	70	1 333.5	–
3	$\mathcal{Q}$	164.5	–	0
4	$\mathcal{Q}$	0	–	0
Generator	Dispatched electricity [MWh]	Dispatched heat [MWh]	Electric surplus [\$]	Heat surplus [\$]
1	104.38	130.58	-3 712.51	5 379.90
2	65.62	33.92	-1 302.82	1 481.58

TABLE VI  
WINTER CA-IHPD RESULTS

$SW = \$6\,934.31 \quad \lambda^{PM} = 45 \$/MWh \quad \gamma^{PM} = 50 \$/MWh$						
User	$u^{pd}$ [\$/MWh]	$u^{cd}$ [\$/MWh]	$v^{pd}$ [\$/MWh]	$v^{cd}$ [\$/MWh]	Electric surplus [\$]	Heat surplus [\$]
1	0	0	–	–	0	–
2	10	0	–	–	0	–
3	–	–	0	0	–	0
4	–	–	0	0	–	0
Generator	$u^{pg}$ [\$/MWh]	$u^{cg}$ [\$/MWh]	$v^{pg}$ [\$/MWh]	$v^{cg}$ [\$/MWh]	Electric surplus [\$]	Heat surplus [\$]
1	1.52	0	0	0	0	5 379.90
2	0	13.08	0	0	72.98	1 481.58