Appendix: Assessing the Impact of Natural Gas and Hydrogen Blending in Integrated Energy System Modeling

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Nomenclature

Sets and Subsets:

rp	Set of representative periods.
k	Set of time step within rp.
g	Set of all generation units t, r, s.
t	Set of thermal generation units.
$\mathcal{T}$	Subset of gas-fired thermal generation units.
r	Set of renewable generation units.
s	Set of storage units in the power system.
i	Sets of power buses.
m,n,l	Sets of gas nodes m, n and pipeline circuits l.
$\mathcal{P}$	Set of pipelines connecting gas nodes (m, n, l).
ch4u	Set of all natural gas units $ch4w, ch4u$.
ch4w	Set of natural gas wells.
ch4s	Set of natural gas storage units.
h2u	Set of all hydrogen units $h2g, h2s, h2p$.
h2g	Set of electrolyzer units.

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h2s	Set of hydrogen storage units.
h2p	Set of steam-methane reforming units.

Parameters:

W_{rp}^{RP}	Weight of representative period.
W_{k}^{K}	Weight of period within representative period.
C^{CH4}	Cost of natural gas.
C_{g}^{OM}	Operation & maintenance cost generation unit.
C_{h2u}^{OM}	Operation & maintenance cost hydrogen unit.
C_{ch4u}^{OM}	Operation & maintenance cost natural gas unit.
C_{g}^{SU}	Startup cost of generation unit.
C_{g}^{UP}	Commitment cost of generation unit.
C_{g}^{VAR}	Variable cost of generating unit.
C^{ENS}	Cost of energy non-supplied.
C^{H2NS}	Cost of hydrogen non-supplied.
C^{CH4NS}	Cost of natural gas non-supplied.
C_{g}^{INV}	Investment cost of generation unit.
C_{h2u}^{INV}	Investment cost of generation unit.
C_{ch4u}^{INV}	Investment cost of natural gas unit.
CS_{t}^{SU}	Startup gas consumption of thermal unit.
CS_{t}^{UP}	Commitment gas consumption of thermal unit.
CS_{t}^{V}	Variable gas consumption of thermal unit.
H^{CH4}	Lower heating value natural gas.
H^{H2}	Lower heating value hydrogen.
EU_{g}	Existing generation units.
EU_{h2u}^{H2}	Existing hydrogen units.
EU_{ch4u}^{CH4}	Existing natural gas units.
$\overline{P}_{h2u}^{E}$	Maximum power capacity of hydrogen unit.
HPE_{h2u}	Hydrogen output per electricity input.
$D_{rp,k,m}^{Gas}$	Gas demand per node.

$\underline{B}^{H2}, \overline{B}^{H2}$	Minimum and maximum hydrogen blend rate.
M	Big-M constant.
$\overline{F}^{Gas}_{m,n,l}$	Maximum pipeline capacity.

Variables:

$p^{CH4}_{rp,k,ch4u}$	Natural gas production of natural gas unit.
$p^{H2}_{rp,k,h2g}$	Hydrogen production of hydrogen unit.
$cs^{E}_{rp,k,h2g}$	Power consumption of hydrogen unit.
$p^{E}_{rp,k,g}$	Power generation of generation unit.
$cs^{H2}_{rp,k,g}$	Hydrogen consumption of generation unit.
$cs^{CH4}_{rp,k,g}$	Natural gas consumption of generation unit.
$d^{H2}_{rp,k,g}$	Share of gas demand covered by hydrogen.
$d^{CH4}_{rp,k,g}$	Share of gas demand covered by natural gas.
$f^{Gas}_{rp,k,m,n,l}$	Pipeline gas flow.
$f^{H2}_{rp,k,m,n,l}$	Pipeline hydrogen flow.
$f^{CH4}_{rp,k,m,n,l}$	Pipeline natural gas flow.
$\alpha^{Gas}_{rp,m,n,l}$	Decision variable for direction of gas flow.
$y_{rp,k,g}$	Startup decision of thermal unit.
$u_{rp,k,g}$	Commitment of thermal unit.
$pns_{rp,k,i}$	Power non-supplied.
$h2ns_{rp,k,m}$	Hydrogen non-supplied.
$ch4ns_{rp,k,m}$	Natural gas non-supplied.
x_{g}	Investment decision generation unit.
x^{H2}_{h2u}	Investment decision hydrogen unit.
x^{CH4}_{ch4u}	Investment decision natural gas unit.

1. Objective Function

$$
\begin{aligned}
min \sum_{rp,k} W_{rp}^{RP} W_k^K \Big(\sum_{ch4w} \underbrace{C^{CH4} p_{rp,k,ch4w}^{CH4}}_{i} + \sum_{t \in \mathcal{T}} \underbrace{C_t^{OM} p_{rp,k,t}^{E}}_{ii} \\
+ \sum_{t \notin \mathcal{T}} \underbrace{(C_t^{SU} y_{rp,k,t} + C_t^{UP} u_{rp,k,t} + C_t^{VAR} p_{rp,k,t}^{E})}_{iii} \\
+ \sum_{r} \underbrace{C_r^{OM} p_{rp,k,r}^{E}}_{iv} + \sum_{s} \underbrace{C_s^{OM} p_{rp,k,s}^{E}}_{v} + \sum_{i} \underbrace{C^{ENS} pns_{rp,k,i}}_{vi} \\
+ \sum_{m} \underbrace{(C^{H2NS} h2ns_{rp,k,m} + C^{CH4NS} ch4ns_{rp,k,m})}_{vii} \Big) \\
+ \sum_{g} \underbrace{C_g^{INV} x_g}_{viii} + \sum_{h2u} \underbrace{(C_{h2u}^{INV} x_{h2u}^{H2})}_{ix} + \underbrace{(C_{h2u}^{OM} (x_{h2u}^{H2} + EU_{h2u}^{H2}))}_{x} \\
+ \sum_{ch4u} \underbrace{(C_{ch4u}^{INV} x_{ch4u}^{CH4})}_{xi} + \underbrace{(C_{ch4u}^{OM} (x_{ch4u}^{CH4} + EU_{ch4u}^{CH4}))}_{xii}
\end{aligned} \tag{1a}
$$

$$
0 \leq pns_{rp,k,i} \leq D_{rp,k,i}^{P} \quad \forall rp, k, i \tag{1b}
$$

$$
0 \leq h2ns_{rp,k,m}, ch4ns_{rp,k,m} \leq M \quad \forall rp, k, m \tag{1c}
$$

$$
\begin{aligned}
x_g, x_{h2u}^{H2}, x_{ch4u}^{CH4} \in \mathbb{Z}^{+,0}, \\
x_g \leq \overline{X}_g, x_{h2u}^{H2} \leq \overline{X}_{h2u}^{H2}, x_{ch4u}^{CH4} \leq \overline{X}_{ch4u}^{CH4} \quad \forall g, h2u, ch4u
\end{aligned} \tag{1d}
$$

2. Power System

2.1. Power Balance & Power Flow

$$
\begin{aligned}
\sum_{gi(t,i)} p_{rp,k,t}^{E} + \sum_{gi(r,i)} p_{rp,k,r}^{E} + \sum_{gi(s,i)} (p_{rp,k,s}^{E} - cs_{rp,k,s}^{E}) \\
+ \sum_{h2ui(h2f,i)} p_{rp,k,h2f}^{E} + \sum_{ijc(j,i,c)} f_{rp,k,j,i,c}^{E} - \sum_{ijc(i,j,c)} f_{rp,k,i,j,c}^{E} \\
+ pns_{rp,k,i} = D_{rp,k,i}^{E} + \sum_{h2ui(h2g,i)} cs_{rp,k,h2g}^{E} \\
+ \sum_{h2ui(h2s,i)} cs_{rp,k,h2s}^{E} \eta_{h2s}^{CH,E} + \sum_{ch4ui(ch4s,i)} cs_{rp,k,ch4s}^{E} \eta_{ch4s}^{CH,E} \quad \forall rp, k, i
\end{aligned} \tag{2a}
$$

$$f^E_{rp,k,ijc} = \frac{(\theta_{rp,k,i} - \theta_{rp,k,j})SB}{Reac_{i,j,c}} \quad \forall rp, k, ijce(i,j,c) \tag{2b}$$

$$-\overline{T}_{i,j,c} \leq f^E_{rp,k,i,j,c} \leq \overline{T}_{i,j,c} \quad \forall rp, k, ijce(i,j,c) \tag{2c}$$

2.2. Renewable Generation Units

$$0 \leq p_{rp,k,r} \leq \overline{P}_r PF_{rp,k,r}(x_r + EU_r) \quad \forall rp, k, r \tag{3a}$$

2.3. Thermal Generation Units

$$p_{rp,k,t} = u_{rp,k,t}\underline{P}_t + \hat{p}_{rp,k,t} \quad \forall rp, k, t \tag{4a}$$

$$\hat{p}_{rp,k,t} + res^+_{rp,k,t} \leq (\overline{P}_t - \underline{P}_t)(u_{rp,k,t} - y_{rp,k,t}) \quad \forall rp, k, t \tag{4b}$$

$$\hat{p}_{rp,k,t} + res^+_{rp,k,t} \leq (\overline{P}_t - \underline{P}_t)(u_{rp,k,t} - z_{rp,k++1,t}) \quad \forall rp, k, t \tag{4c}$$

$$\hat{p}_{rp,k,t} \geq res^-_{rp,k,t} \quad \forall rp, k, t \tag{4d}$$

$$u_{rp,k,t} - u_{rp,k--1,t} = y_{rp,k,t} - z_{rp,k,t} \quad \forall rp, k, t \tag{4e}$$

$$u_{rp,k,t} \leq x_t + EU_t \quad \forall rp, k, t \tag{4f}$$

$$\hat{p}_{rp,k,t} - \hat{p}_{rp,k--1,t} + res^+_{rp,k,t} \leq u_{rp,k,t} RU_t \quad \forall rp, k, t \tag{4g}$$

$$\hat{p}_{rp,k,t} - \hat{p}_{rp,k--1,t} - res^-_{rp,k,t} \geq -u_{rp,k--1,t} RD_t \quad \forall rp, k, t \tag{4h}$$

$$0 \leq p_{rp,k,t} \leq \overline{P}_t(x_t + EU_t) \quad \forall rp, k, t \tag{4i}$$

$$0 \leq \hat{p}_{rp,k,t}, res^-_{rp,k,t}, res^+_{rp,k,t} \leq (\overline{P}_t - \underline{P}_t)(x_t + EU_t) \quad \forall rp, k, t \tag{4j}$$

$$u_{rp,k,t}, y_{rp,k,t}, z_{rp,k,t} \in \{0, 1\} \quad \forall rp, k, t \tag{4k}$$

2.4. Reserve Constraint

$$\sum_t res^+_{rp,k,t} + \sum_s res^+_{rp,k,s} \geq RES^+ \sum_i D^P_{rp,k,i} \quad \forall rp, k \tag{5a}$$

$$\sum_t res^-_{rp,k,t} + \sum_s res^-_{rp,k,s} \geq RES^- \sum_i D^P_{rp,k,i} \quad \forall rp, k \tag{5b}$$

3. Gas System

3.1. Hydrogen & Natural Gas Balance

$$\sum_{h2um(h2g,m)} p^{H2}_{rp,k,h2g} + \sum_{h2um(h2p,m)} p^{H2}_{rp,k,h2p} + \sum_{h2um(h2s,m)} p^{H2}_{rp,k,h2s}$$
$$+h2ns_{rp,k,m} + \sum_{mnl(m,n,l)} f^{H2}_{rp,k,m,n,l} - \sum_{mnl(m,n,l)} f^{H2}_{rp,k,m,n,l}$$
$$+ \sum_{cmp(m,n,l)} f^{Cmp,H2}_{rp,k,m,n,l} - \sum_{cmp(m,n,l)} f^{Cmp,H2}_{rp,k,m,n,l} = D^{H2}_{rp,k,m} + d^{Gas,H2}_{rp,k,m}$$
$$+ \sum_{h2um(h2f,m)} cs^{H2}_{rp,k,h2f} + \sum_{h2um(h2s,m)} cs^{H2}_{rp,k,h2s} + \sum_{gm(\mathcal{T}\in gas,m)} cs^{H2}_{rp,k,t}$$
$$+ \sum_{cmp(m,n,l)} CS^{Cmp,H2}_{m,n,l} f^{Cmp,H2}_{rp,k,m,n,l} \quad \forall rp,k,m \tag{6a}$$

$$\sum_{ch4um(ch4w,m)} p^{CH4}_{rp,k,ch4w} + \sum_{ch4um(ch4s,m)} p^{CH4}_{rp,k,ch4s} + \sum_{mnl(m,n,l)} f^{CH4}_{rp,k,m,n,l}$$
$$- \sum_{mnl(m,n,l)} f^{CH4}_{rp,k,m,n,l} + \sum_{cmp(m,n,l)} f^{Cmp,CH4}_{rp,k,m,n,l} - \sum_{cmp(m,n,l)} f^{Cmp,CH4}_{rp,k,m,n,l}$$
$$+ch4ns_{rp,k,m} = d^{CH4}_{rp,k,m} + \sum_{gm(\mathcal{T}\in gas,m)} cs^{CH4}_{rp,k,t} + \sum_{ch4um(ch4s,m)} cs^{CH4}_{rp,k,ch4s}$$
$$+ \sum_{ch4um(h2p,m)} cs^{CH4}_{rp,k,h2p} + \sum_{cmp(m,n,l)} CS^{Cmp,CH4}_{m,n,l} f^{Cmp,CH4}_{rp,k,m,n,l} \quad \forall rp,k,m \tag{6b}$$

$$0 \leq f^{Cmp,CH4}_{rp,k,m,n,l} + f^{Cmp,H2}_{rp,k,m,n,l} \leq \overline{F}^{Cmp,Gas}_{m,n,l} \quad \forall rp,k,\mathcal{P} \tag{6c}$$
$$0 \leq f^{Cmp,H2}_{rp,k,m,n,l} \leq f^{Cmp,CH4}_{rp,k,m,n,l} \overline{B}^{H2} \quad \forall rp,k,\mathcal{P} \tag{6d}$$

3.2. Blending Transport Problem (B-TP)

$$f^{Gas}_{rp,k,m,n,l} = f^{CH4}_{rp,k,m,n,l} + f^{H2}_{rp,k,m,n,l} \quad \forall rp,k,\mathcal{P} \tag{7a}$$
$$(\alpha^{Gas}_{rp,m,n,l} - 1)M \leq f^{H2}_{rp,k,m,n,l} \leq \alpha^{Gas}_{rp,m,n,l} M \quad \forall rp,k,\mathcal{P} \tag{7b}$$
$$(\alpha^{Gas}_{rp,m,n,l} - 1)M \leq f^{CH4}_{rp,k,m,n,l} \leq \alpha^{Gas}_{rp,m,n,l} M \quad \forall rp,k,\mathcal{P} \tag{7c}$$
$$f^{H2}_{rp,k,m,n,l} \geq -\alpha^{Gas}_{rp,m,n,l} M + \overline{B}^{H2} f^{CH4}_{rp,k,m,n,l} \quad \forall rp,k,\mathcal{P} \tag{7d}$$
$$(1 - \alpha^{Gas}_{rp,m,n,l})M + \overline{B}^{H2} f^{CH4}_{rp,k,m,n,l} \geq f^{H2}_{rp,k,m,n,l} \quad \forall rp,k,\mathcal{P} \tag{7e}$$

$$-\overline{F}^{Gas}_{m,n,l} \leq f^{Gas}_{rp,k,m,n,l} \leq \overline{F}^{Gas}_{m,n,l} \quad \forall rp, k, \mathcal{P} \tag{7f}$$

3.3. Standard Transport Problem (S-TP)

$$-\overline{F}^{Gas}_{m,n,l}\overline{B}^{H2} \leq f^{H2}_{rp,k,m,n,l} \leq \overline{F}^{Gas}_{m,n,l}\overline{B}^{H2} \quad \forall rp, k, \mathcal{P} \tag{8a}$$

$$-\overline{F}^{Gas}_{m,n,l}(1-\overline{B}^{H2}) \leq f^{CH4}_{rp,k,m,n,l} \leq \overline{F}^{Gas}_{m,n,l}(1-\overline{B}^{H2}) \quad \forall rp, k, \mathcal{P} \tag{8b}$$

3.4. Gas-fired Thermal Units

$$cs^{CH4}_{rp,k,t}H^{CH4} + cs^{H2}_{rp,k,t}H^{H2} =$$

$$(CS^{SU}_t y_{rp,k,t} + CS^{UP}_t u_{rp,k,t} + CS^{V}_t p^{E}_{rp,k,t}) \quad \forall rp, k, t \in \mathcal{T} \tag{9a}$$

$$0 \leq cs^{CH4}_{rp,k,t} \leq (CS^{UP}_t + CS^{V}_t \overline{P}^{E}_{rp,k,t})$$

$$(1/H^{CH4})(x_t + EU_t) \quad \forall rp, k, t \in \mathcal{T} \tag{9b}$$

$$0 \leq p^{E}_{rp,k,t} \leq \overline{P}^{E}_t (x_t + EU_t) \quad \forall rp, k, t \in \mathcal{T} \tag{9c}$$

$$\underline{B}^{H2} cs^{CH4}_{rp,k,t} \leq cs^{H2}_{rp,k,t} \leq \overline{B}^{H2} cs^{CH4}_{rp,k,t} \quad \forall rp, k, t \in \mathcal{T} \tag{9d}$$

3.5. Natural Gas Storage Units

$$intra^{CH4}_{rp,k,ch4s} = intra^{CH4}_{rp,k--1,ch4s} - p^{CH4}_{rp,k,ch4s} W^{K}_k / \eta^{DIS}_{ch4s} +$$

$$+ cs^{CH4}_{rp,k,ch4s} W^{K}_k \eta^{CH}_{ch4s} \quad \forall rp, k, ch4s \tag{10a}$$

$$intra^{CH4}_{rp,k,ch4s} \geq \underline{R}_{ch4s} \overline{P}_{ch4s} ETP_{ch4s} (x^{CH4}_{ch4s} + EU^{CH4}_{ch4s})$$

$$\forall rp, k, ch4s \tag{10b}$$

$$intra^{CH4}_{rp,k,ch4s} \leq \overline{P}_{ch4s} ETP_{ch4s} (x^{CH4}_{ch4s} + EU^{CH4}_{ch4s})$$

$$\forall rp, k, ch4s \tag{10c}$$

$$inter^{CH4}_{p,ch4s} = inter^{CH4}_{p-MOW,ch4s} +$$

$$+ InRes^{CH4}_{ch4s,p=MOW} (x^{CH4}_{ch4s} + EU^{CH4}_{ch4s})$$

$$+ \sum_{\Gamma(p-MOW \leq pp \leq p, rp, k)} (-p^{CH4}_{rp,k,ch4s} W^{K}_k / \eta^{DIS}_{ch4s} +$$

$$+cs^{CH4}_{rp,k,ch4s}W^K_k\eta^{CH}_{ch4s}) \quad \forall p, ch4s \tag{10d}$$

$$inter^{CH4}_{p,ch4s} \leq \overline{P}_{ch4s}ETP_{ch4s}(x^{CH4}_{ch4s} + EU^{CH4}_{ch4s})$$

$$\forall ch4s, p : mod(p, MOW) = 0 \tag{10e}$$

$$inter^{CH4}_{p,ch4s} \geq \underline{R}_{ch4s}\overline{P}_{ch4s}ETP_{ch4s}(x^{CH4}_{ch4s} + EU^{CH4}_{ch4s})$$

$$\forall ch4s, p : mod(p, MOW) = 0 \tag{10f}$$

$$inter^{CH4}_{p,ch4s} \geq InRes^{CH4}_{ch4s}(x^{CH4}_{ch4s} + EU^{CH4}_{ch4s})$$

$$\forall ch4s, p = CARD(p) \tag{10g}$$

$$0 \leq p^{CH4}_{rp,k,ch4s} \leq \overline{P}_{ch4s}(x^{CH4}_{ch4s} + EU^{CH4}_{ch4s}) \quad \forall rp, k, ch4s \tag{10h}$$

$$0 \leq cs^{CH4}_{rp,k,ch4s} \leq \overline{CS}_{ch4s}(x^{CH4}_{ch4s} + EU^{CH4}_{ch4s}) \quad \forall rp, k, ch4s \tag{10i}$$

3.6. Natural Gas Wells

$$0 \leq p^{CH4}_{rp,k,ch4w} \leq \overline{P}_{ch4w}(x^{CH4}_{ch4w} + EU^{CH4}_{ch4w}) \quad \forall rp, k, ch4w \tag{11a}$$

3.7. Electrolyzer Units

$$p^{H2}_{rp,k,h2g} = cs^{E}_{rp,k,h2g}HPE_{h2g} \quad \forall rp, k, h2g \tag{12a}$$

$$0 \leq cs^{E}_{rp,k,h2g} \leq \overline{P}^{E}_{h2g}(x^{H2}_{h2g} + EU^{H2}_{h2g}) \quad \forall rp, k, h2g \tag{12b}$$

$$0 \leq p^{H2}_{rp,k,h2g} \leq \overline{P}^{E}_{h2g}HPE_{h2g}(x^{H2}_{h2g} + EU^{H2}_{h2g}) \quad \forall rp, k, h2g \tag{12c}$$

3.8. Steam-Methane Reforming Units

$$p^{H2}_{rp,k,h2p} = cs^{CH4}_{rp,k,h2p}HPC_{h2p} \quad \forall rp, k, h2p \tag{13a}$$

$$0 \leq cs^{CH4}_{rp,k,h2p} \leq \overline{P}^{H2}_{h2p}(x^{H2}_{h2p} + EU^{H2}_{h2p}) \quad \forall rp, k, h2p \tag{13b}$$

$$0 \leq p^{H2}_{rp,k,h2p} \leq \overline{P}^{H2}_{h2p}HPC_{h2p}(x^{H2}_{h2p} + EU^{H2}_{h2p}) \quad \forall rp, k, h2p \tag{13c}$$

3.9. Hydrogen Storage Units

$$intra^{H2}_{rp,k,h2s} = intra^{H2}_{rp,k--1,h2s} - p^{H2}_{rp,k,h2s} W^{K}_{k} / \eta^{DIS}_{h2s} + cs^{H2}_{rp,k,h2s} W^{K}_{k} \eta^{CH}_{h2s} \quad \forall rp, k, h2s \tag{14a}$$

$$\underline{R}_{h2s} \overline{P}_{h2s} ETP_{h2s} (x^{H2}_{h2s} + EU^{H2}_{h2s}) \le intra^{H2}_{rp,k,h2s} \le \overline{P}_{h2s} ETP_{h2s} (x^{H2}_{h2s} + EU^{H2}_{h2s}) \quad \forall rp, k, h2s \tag{14b}$$

$$\begin{aligned} inter^{H2}_{p,h2s} &= inter^{H2}_{p-MOW,h2s} + InRes^{H2}_{h2s,p=MOW} (x^{H2}_{h2s} + EU^{H2}_{h2s}) \\ &+ \sum_{\Gamma(p-MOW \le pp \le p, rp, k)} (-p^{H2}_{rp,k,h2s} W^{K}_{k} / \eta^{DIS}_{h2s} + cs^{H2}_{rp,k,h2s} W^{K}_{k} \eta^{CH}_{h2s}) \quad \forall p, h2s \end{aligned} \tag{14c}$$

$$inter^{H2}_{p,h2s} \le \overline{P}_{h2s} ETP_{h2s} (x^{H2}_{h2s} + EU^{H2}_{h2s}) \quad \forall h2s, p : mod(p, MOW) = 0 \tag{14d}$$

$$inter^{H2}_{p,h2s} \ge \underline{R}_{h2s} \overline{P}_{h2s} ETP_{h2s} (x^{H2}_{h2s} + EU^{H2}_{h2s}) \quad \forall h2s, p : mod(p, MOW) = 0 \tag{14e}$$

$$inter^{H2}_{p,h2s} \ge InRes^{H2}_{h2s} (x^{H2}_{h2s} + EU^{H2}_{h2s}) \quad \forall h2s, p = CARD(p) \tag{14f}$$

$$0 \le p^{H2}_{rp,k,h2s} \le \overline{P}_{h2s} (x^{H2}_{h2s} + EU^{H2}_{h2s}) \quad \forall rp, k, h2s \tag{14g}$$

$$0 \le cs^{H2}_{rp,k,h2s} \le \overline{CS}_{h2s} (x^{H2}_{h2s} + EU^{H2}_{h2s}) \quad \forall rp, k, h2s \tag{14h}$$

3.10. Gas Demand Blending

$$D^{Gas}_{rp,k,m} H^{CH4} = d^{CH4}_{rp,k,m} H^{CH4} + d^{H2}_{rp,k,m} H^{H2} \quad \forall rp, k, m \tag{15a}$$

$$0 \le d^{CH4}_{rp,k,m} \le D^{Gas}_{rp,k,m} \quad \forall rp, k, m \tag{15b}$$

$$\underline{B}^{H2} d^{CH4}_{rp,k,m} \le d^{H2}_{rp,k,m} \le \overline{B}^{H2} d^{CH4}_{rp,k,m} \quad \forall rp, k, m \tag{15c}$$