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

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Nomenclature

Sets and Subsets:

p	Set of time periods.
rp	Set of representative periods.
k	Set of time step within rp.
$\Gamma(p, rp, k)$	Mapping of periods with representative periods rp and k.
g	Set of all generation units t, r, s.
t	Subset of thermal generation units.
r	Subset of renewable generation units.
s	Subset of storage units in the power system.
i,j,c	Sets of power buses i, j and power line circuits c.
ijc(i,j,c)	Set of power lines connecting i and j via circuit c.
gi(g,i)	Set of g connected to i.
m,n,l	Sets of gas nodes m, n and pipeline circuits l.
a(m,n,l)	Set of pipelines connecting m and n via circuit l.
gm(g,m)	Set of g connected to m.
cmp(m,n,l)	Set of compressor units connecting m and n.

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ch4u	Set of all natural gas units $ch4w, ch4u$.
ch4w	Subset of natural gas wells.
ch4s	Subset of natural gas storage units.
h2u	Set of all hydrogen units $h2g, h2s, h2p$.
h2g	Subset of electrolyzer units.
h2s	Subset of hydrogen storage units.
h2p	Subset of steam-methane reforming units.
h2um(h2u,m)	Set of $h2u$ connected to m.
h2ui(h2u,i)	Set of $h2u$ connected to i.
ch4um(ch4u,m)	Set of $ch4u$ connected to m.
ch4ui(ch4u,i)	Set of $ch4u$ connected to i.

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.
$\overline{X}_g$	Maximum amount of installable generation unit.
$\overline{X}_{h2u}^{H2}$	Maximum amount of installable hydrogen unit.
$\overline{X}_{ch4u}^{CH4}$	Maximum amount of installable natural gas unit.
$\overline{P}_g^E$	Maximum power capacity of generation unit.
$\underline{P}_g^E$	Technical minimum power capacity of generation unit.
$\overline{P}_{h2u}^E$	Maximum power capacity of hydrogen unit.
$\overline{P}_{h2u}^{H2}$	Maximum hydrogen production capacity of hydrogen unit.
$\overline{P}_{ch4u}^{CH4}$	Maximum natural gas production capacity of natural gas unit.
$\overline{CS}_{h2u}^{H2}$	Maximum hydrogen consumption capacity of hydrogen unit.
$\overline{CS}_{ch4u}^{CH4}$	Maximum natural gas consumption capacity of natural gas unit.
$\underline{R}_{h2u}^{H2}$	Minimum hydrogen reserve hydrogen unit.
$\underline{R}_{ch4u}^{CH4}$	Minimum natural gas reserve natural gas unit.
HPE_{h2u}	Hydrogen output per electricity input.
HPC_{ch4u}	Hydrogen output per natural gas input.
ETP_{ch4u}	Energy to power ration natural gas unit.
ETP_{h2u}	Energy to power ration hydrogen unit.
$InRes_{ch4u}^{CH4}$	Initial reserve of natural gas unit.
$InRes_{h2u}^{H2}$	Initial reserve of hydrogen unit.
$D_{rp,k,i}^E$	Power demand per bus.
$D_{rp,k,m}^{Gas}$	Gas demand per node.
$D_{rp,k,m}^{H2}$	Hydrogen demand per node.
$\eta_{h2u}^{CH,E}$	Electrical charging efficiency of hydrogen unit.
$\eta_{ch4u}^{CH,E}$	Electrical charging efficiency of natural gas unit.
$\eta_{h2u}^{CH}, \eta_{h2u}^{DIS}$	Hydrogen charging and discharging efficiency of hydrogen unit.

$\eta^{CH}_{ch4u}, \eta^{DIS}_{ch4u}$	Natural gas charging and discharging efficiency of natural gas unit.
SB	Base power (MVA).
$Reac_{i,j,c}$	Reactance of power line.
$\overline{T}_{i,j,c}$	Capacity of transmission line.
$\overline{P}_g$	Maximum power capacity of generation unit.
$PF_{rp,k,i,r}$	Renewable profile per unit and node.
RU_g	Ramp-up limit of generation unit
RD_g	Ramp-down limit of generation unit
MOW	Moving window for long-term storage
$\underline{B}^{H2}, \overline{B}^{H2}$	Minimum and maximum hydrogen blend rate.
M	Big-M constant.
$\overline{F}^{Gas}_{m,n,l}$	Maximum pipeline capacity.
$\overline{F}^{Cmp,Gas}_{m,n,l}$	Maximum compressor capacity.
$CS^{Cmp,CH4}_{m,n,l}$	Compressor natural gas consumption.
$CS^{Cmp,H2}_{m,n,l}$	Compressor hydrogen consumption.

Variables:

$p^{CH4}_{rp,k,ch4u}$	Natural gas production of natural gas unit.
$p^{H2}_{rp,k,h2u}$	Hydrogen production of hydrogen unit.
$cs^{E}_{rp,k,h2u}$	Power consumption of hydrogen unit.
$cs^{E}_{rp,k,ch4u}$	Power consumption of natural gas unit.
$p^{E}_{rp,k,g}$	Power generation of generation unit.
$\hat{p}^{E}_{rp,k,g}$	Power generation above the technical minimum.
$cs^{E}_{rp,k,g}$	Power consumption of generation unit.
$cs^{H2}_{rp,k,g}$	Hydrogen consumption of generation unit.
$cs^{CH4}_{rp,k,g}$	Natural gas consumption of generation unit.
$cs^{H2}_{rp,k,h2u}$	Hydrogen consumption of hydrogen unit.
$cs^{H2}_{rp,k,ch4u}$	Hydrogen consumption of natural gas unit.
$cs^{CH4}_{rp,k,ch4u}$	Natural gas consumption of natural gas 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.
$f^{Cmp,H2}_{rp,k,m,n,l}$	Compressor hydrogen flow.
$f^{CH4}_{rp,k,m,n,l}$	Pipeline natural gas flow.
$f^{Cmp,CH4}_{rp,k,m,n,l}$	Compressor natural gas flow.
$f^{E}_{rp,k,i,j,c}$	Power flow.
$\theta_{rp,k,i}$	Power flow angle.
$\alpha^{Gas}_{rp,m,n,l}$	Decision variable for direction of gas flow.
$y_{rp,k,g}$	Startup decision of thermal unit.
$u_{rp,k,g}$	Commitment of thermal unit.
$z_{rp,k,g}$	Shutdown decision of thermal unit.
$intra^{CH4}_{rp,k,ch4u}$	Intra-period state of charge of natural gas unit.
$inter^{CH4}_{p,ch4u}$	Inter-period state of charge of natural gas unit.
$intra^{H2}_{rp,k,h2u}$	Intra-period state of charge of hydrogen unit.
$inter^{H2}_{p,h2u}$	Inter-period state of charge of hydrogen 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

The objective function (1a) comprises total system costs: (*i*) cost of natural gas supply to the system; (*ii*) operation and maintenance (OM) costs cost of gas-fired thermal units; (*iii*) unit commitment costs of thermal units (except gas-fired thermal units); (*iv*) OM costs of renewable units; (*v*) OM costs of storage units (power system); (*vi*) energy non-supplied; (*vii*) H_2 and natural gas non-supplied; (*viii*) investment costs for power generation units; (*ix*) investment costs for H_2 units; (*x*) OM costs for H_2 units; (*xi*) investment costs for natural gas units; and (*xii*) OM costs for natural gas units. The system-wide natural gas demand is met from gas wells (*i*). Thus, the unit commitment costs (except for OM costs (*ii*) of CCGTs and OCGTs), costs for natural gas consumption from SMR units, and costs of meeting natural gas demand other than for power generation are accounted for implicitly. Constraints (1b-1c) establish lower and upper bounds for power, H_2, and natural gas non-supplied, while (1d) limits the investments in generation, H_2, and natural gas units and establishes non-negativity.

$$
\begin{aligned}
min \sum_{rp,k} W^{RP}_{rp} W^{K}_{k} \Big(& \sum_{ch4w} \underbrace{C^{CH4} p^{CH4}_{rp,k,ch4w}}_{i} + \sum_{t=gas} \underbrace{C^{OM}_{t} p^{E}_{rp,k,t}}_{ii} \\
& + \sum_{t \neq gas} \underbrace{(C^{SU}_{t} y_{rp,k,t} + C^{UP}_{t} u_{rp,k,t} + C^{VAR}_{t} p^{E}_{rp,k,t})}_{iii} \\
& + \sum_{r} \underbrace{C^{OM}_{r} p^{E}_{rp,k,r}}_{iv} + \sum_{s} \underbrace{C^{OM}_{s} p^{E}_{rp,k,s}}_{v} + \sum_{i} \underbrace{C^{ENS} pns_{rp,k,i}}_{vi} \\
& + \sum_{m} \underbrace{(C^{H2NS} h2ns_{rp,k,m} + C^{CH4NS} ch4ns_{rp,k,m})}_{vii} \Big) \\
& + \sum_{g} \underbrace{C^{INV}_{g} x_{g}}_{viii} + \sum_{h2u} \underbrace{(C^{INV}_{h2u} x^{H2}_{h2u})}_{ix} + \underbrace{(C^{OM}_{h2u} (x^{H2}_{h2u} + EU^{H2}_{h2u}))}_{x} \\
& + \sum_{ch4u} \underbrace{(C^{INV}_{ch4u} x^{CH4}_{ch4u})}_{xi} + \underbrace{(C^{OM}_{ch4u} (x^{CH4}_{ch4u} + EU^{CH4}_{ch4u}))}_{xii}
\end{aligned} \tag{1a}
$$

$$0 \leq pns_{rp,k,i} \leq D^{E}_{rp,k,i} \quad \forall rp, k, i \tag{1b}$$

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

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

2. Power System

2.1. Power Balance & Power Flow

The power system is governed by the power balance equation (2a) comprising power generation of all units t, r, and s, charging of power storage units s, auxiliary power required for charging of H_2 units *h2s*, power demand, and power non-supplied. Constraints (2b-2c) represent the power flow as DC-OPF.

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

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

$$-\overline{T}_{i,j,c} \leq f_{rp,k,i,j,c}^{E} \leq \overline{T}_{i,j,c} \quad \forall rp, k, ijc(i,j,c) \tag{2c}$$

2.2. Renewable Generation Units

Constraint (3) describes renewable generation units (wind, solar) based on renewable profiles (capacity factors).

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

2.3. Thermal Generation Units

Constraints (4) describe all thermal generation units and include unit commitment constraints. Gas-fired thermal generators are subject to additional constraints (9).

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

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

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

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

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

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

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

$$0 \leq p^E_{rp,k,t} \leq \overline{P}^E_t(x_t + EU_t) \quad \forall rp,k,t \tag{4h}$$

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

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

3. Gas System

3.1. Natural Gas & Hydrogen Balance

The natural gas and H_2 sectors are established by two separate balance equations, which are both very similar in their structure. The natural gas balance (5a) comprises: production from gas wells and storage units; the variable share of gas demand outside the power sector that can be supplied by natural gas; the natural gas consumption from gas-fired thermals, storage, SMR, and compressor units; and natural gas non-supplied. The H_2 balance (5b) comprises: production form EL, SMR, and storage units; the variable share of gas demand outside the power sector that can be supplied by H_2 as well as a dedicated H_2 demand; the H_2 consumption from gas-fired thermals, storage, and compressor units; and H_2 non-supplied. Furthermore, both balances include gas flows through pipelines and compressor units governed by (5c-5d).

$$\begin{aligned}
&\sum_{ch4um(ch4w,m)} p^{CH4}_{rp,k,ch4w} + \sum_{ch4um(ch4s,m)} p^{CH4}_{rp,k,ch4s} + \sum_{mnl(n,m,l)} f^{CH4}_{rp,k,m,n,l} \\
&- \sum_{mnl(m,n,l)} f^{CH4}_{rp,k,m,n,l} + \sum_{cmp(n,m,l)} f^{Cmp,CH4}_{rp,k,m,n,l} - \sum_{cmp(m,n,l)} f^{Cmp,CH4}_{rp,k,m,n,l} \\
&+ch4ns_{rp,k,m} = d^{CH4}_{rp,k,m} + \sum_{gm(t\in\mathcal{T},m)} cs^{CH4}_{rp,k,t} + \sum_{ch4um(ch4s,m)} cs^{CH4}_{rp,k,ch4s} \\
&+ \sum_{ch4um(h2p,m)} cs^{CH4}_{rp,k,h2p} + \sum_{cmp(m,n,l)} CS^{Cmp,CH4}_{m,n,l} f^{Cmp,CH4}_{rp,k,m,n,l} \quad \forall rp,k,m
\end{aligned} \tag{5a}$$

$$\begin{aligned}
&\sum_{h2um(h2g,m)} p^{H2}_{rp,k,h2g} + \sum_{h2um(h2p,m)} p^{H2}_{rp,k,h2p} + \sum_{h2um(h2s,m)} p^{H2}_{rp,k,h2s} \\
&+h2ns_{rp,k,m} + \sum_{mnl(n,m,l)} f^{H2}_{rp,k,m,n,l} - \sum_{mnl(m,n,l)} f^{H2}_{rp,k,m,n,l} \\
&+ \sum_{cmp(n,m,l)} f^{Cmp,H2}_{rp,k,m,n,l} - \sum_{cmp(m,n,l)} f^{Cmp,H2}_{rp,k,m,n,l} = D^{H2}_{rp,k,m} + d^{Gas,H2}_{rp,k,m} \\
&+ \sum_{h2um(h2s,m)} cs^{H2}_{rp,k,h2s} + \sum_{gm(t\in\mathcal{T},m)} cs^{H2}_{rp,k,t} \\
&+ \sum_{cmp(m,n,l)} CS^{Cmp,H2}_{m,n,l} f^{Cmp,H2}_{rp,k,m,n,l} \quad \forall rp,k,m
\end{aligned} \tag{5b}$$

$$0 \le f^{Cmp,CH4}_{rp,k,m,n,l} + f^{Cmp,H2}_{rp,k,m,n,l} \le \overline{F}^{Cmp,Gas}_{m,n,l} \quad \forall rp,k,cmp(m,n,l) \tag{5c}$$

$$0 \le f^{Cmp,H2}_{rp,k,m,n,l} \le f^{Cmp,CH4}_{rp,k,m,n,l} \overline{B}^{H2} \quad \forall rp,k,cmp(m,n,l) \tag{5d}$$

3.2. Blending Transport Problem (B-TP)

Constraints (6a-6f) govern the novel blending transport problem.

$$f^{Gas}_{rp,k,m,n,l} = f^{CH4}_{rp,k,m,n,l} + f^{H2}_{rp,k,m,n,l} \quad \forall rp,k,a \tag{6a}$$

$$(\alpha^{Gas}_{rp,m,n,l} - 1)M \le f^{H2}_{rp,k,m,n,l} \le \alpha^{Gas}_{rp,m,n,l} M \quad \forall rp,k,a \tag{6b}$$

$$(\alpha^{Gas}_{rp,m,n,l} - 1)M \le f^{CH4}_{rp,k,m,n,l} \le \alpha^{Gas}_{rp,m,n,l} M \quad \forall rp,k,a \tag{6c}$$

$$f^{H2}_{rp,k,m,n,l} \ge -\alpha^{Gas}_{rp,m,n,l} M + \overline{B}^{H2} f^{CH4}_{rp,k,m,n,l} \quad \forall rp,k,a \tag{6d}$$

$$(1 - \alpha^{Gas}_{rp,m,n,l})M + \overline{B}^{H2} f^{CH4}_{rp,k,m,n,l} \ge f^{H2}_{rp,k,m,n,l} \quad \forall rp,k,a \tag{6e}$$

$$-\overline{F}^{Gas}_{m,n,l} \le f^{Gas}_{rp,k,m,n,l} \le \overline{F}^{Gas}_{m,n,l} \quad \forall rp,k,a \tag{6f}$$

3.3. Standard Transport Problem (S-TP)

Constraints (7b-7b) govern the standard transport problem.

$$-\overline{F}^{Gas}_{m,n,l}\overline{B}^{H2} \leq f^{H2}_{rp,k,m,n,l} \leq \overline{F}^{Gas}_{m,n,l}\overline{B}^{H2} \quad \forall rp, k, a \tag{7a}$$

$$-\overline{F}^{Gas}_{m,n,l}(1-\overline{B}^{H2}) \leq f^{CH4}_{rp,k,m,n,l} \leq \overline{F}^{Gas}_{m,n,l}(1-\overline{B}^{H2}) \quad \forall rp, k, a \tag{7b}$$

3.4. Gas Demand Blending

Constraints (8) describe the gas demand including blending of natural gas and H_2.

$$D^{Gas}_{rp,k,m}H^{CH4} = d^{CH4}_{rp,k,m}H^{CH4} + d^{H2}_{rp,k,m}H^{H2} \quad \forall rp, k, m \tag{8a}$$

$$0 \leq d^{CH4}_{rp,k,m} \leq D^{Gas}_{rp,k,m} \quad \forall rp, k, m \tag{8b}$$

$$\underline{B}^{H2}d^{CH4}_{rp,k,m} \leq d^{H2}_{rp,k,m} \leq \overline{B}^{H2}d^{CH4}_{rp,k,m} \quad \forall rp, k, m \tag{8c}$$

3.5. Gas-fired Thermal Units

Constraints (9a-9c) describes the gas consumption and power output of gas-fired generators during startup, commitment, and power generation. Constraint (9d) describe natural gas and H_2 blending in case of co-firing by CCGTs and OCGTs.

$$cs^{CH4}_{rp,k,t}H^{CH4} + cs^{H2}_{rp,k,t}H^{H2} = (CS^{SU}_t y_{rp,k,t} + CS^{UP}_t u_{rp,k,t} + CS^V_t p^E_{rp,k,t}) \quad \forall rp, k, t = gas \tag{9a}$$

$$0 \leq cs^{CH4}_{rp,k,t} \leq (CS^{UP}_t + CS^V_t\overline{P}^E_{rp,k,t})(1/H^{CH4})(x_t + EU_t) \quad \forall rp, k, t = gas \tag{9b}$$

$$0 \leq p^E_{rp,k,t} \leq \overline{P}^E_t(x_t + EU_t) \quad \forall rp, k, t = gas \tag{9c}$$

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

3.6. Natural Gas Storage Units

Constraints (10a-10i) describe (long-term) natural gas storage units based on a state of charge (SOC) concept. In case the model is run based on representative periods, constraints (10a-10c) describe the intra-period SOC of storage units and (10d-10g) describe the inter-period SOC of long-term storage units. In case the model is run based on a full chronological time series (which corresponds to a single representative period), all storage units are governed by the intra-period SOC.

$$\begin{aligned} intra^{CH4}_{rp,k,ch4s} = intra^{CH4}_{rp,k--1,ch4s} - p^{CH4}_{rp,k,ch4s} W^{K}_{k} / \eta^{DIS}_{ch4s} + \\ + cs^{CH4}_{rp,k,ch4s} W^{K}_{k} \eta^{CH}_{ch4s} \quad \forall rp, k, ch4s \end{aligned} \tag{10a}$$

$$\begin{aligned} intra^{CH4}_{rp,k,ch4s} \geq \underline{R}^{CH4}_{ch4s} \overline{P}^{CH4}_{ch4s} ETP_{ch4s} (x^{CH4}_{ch4s} + EU^{CH4}_{ch4s}) \\ \forall rp, k, ch4s \end{aligned} \tag{10b}$$

$$\begin{aligned} intra^{CH4}_{rp,k,ch4s} \leq \overline{P}^{CH4}_{ch4s} ETP_{ch4s} (x^{CH4}_{ch4s} + EU^{CH4}_{ch4s}) \\ \forall rp, k, ch4s \end{aligned} \tag{10c}$$

$$\begin{aligned} inter^{CH4}_{p,ch4s} = inter^{CH4}_{p-MOW,ch4s} + \\ + InRes^{CH4}_{ch4s,p=MOW} (x^{CH4}_{ch4s} + EU^{CH4}_{ch4s}) \\ + \sum_{\Gamma(p-MOW \leq pp \leq p, rp, k)} (-p^{CH4}_{rp,k,ch4s} W^{K}_{k} / \eta^{DIS}_{ch4s} + \\ + cs^{CH4}_{rp,k,ch4s} W^{K}_{k} \eta^{CH}_{ch4s}) \quad \forall p, ch4s \end{aligned} \tag{10d}$$

$$\begin{aligned} inter^{CH4}_{p,ch4s} \leq \overline{P}^{CH4}_{ch4s} ETP_{ch4s} (x^{CH4}_{ch4s} + EU^{CH4}_{ch4s}) \\ \forall ch4s, p : mod(p, MOW) = 0 \end{aligned} \tag{10e}$$

$$\begin{aligned} inter^{CH4}_{p,ch4s} \geq \underline{R}^{CH4}_{ch4s} \overline{P}^{CH4}_{ch4s} ETP_{ch4s} (x^{CH4}_{ch4s} + EU^{CH4}_{ch4s}) \\ \forall ch4s, p : mod(p, MOW) = 0 \end{aligned} \tag{10f}$$

$$\begin{aligned} inter^{CH4}_{p,ch4s} \geq InRes^{CH4}_{ch4s} (x^{CH4}_{ch4s} + EU^{CH4}_{ch4s}) \\ \forall ch4s, p = CARD(p) \end{aligned} \tag{10g}$$

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

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

3.7. Natural Gas Wells

Gas wells (11) supply natural gas to the system.

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

3.8. Electrolyzer Units

Constraints (12) describe electrolyzer units. Constraint (12a) describes the relation between hydrogen production and electricity consumption, while (12b-12c) establish lower and upper bounds on these variables.

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

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

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

3.9. Steam-Methane Reforming Units

SMR units (13) follow the same modeling principle as electrolyzer units but establish a relation between natural gas consumption and H_2 production.

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

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

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

3.10. Hydrogen Storage Units

Hydrogen storage units follow the same concept as natural gas storage units (see section 3.6).

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

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

$$inter^{H2}_{p,h2s} = inter^{H2}_{p-MOW,h2s} + InRes^{H2}_{h2s,p=MOW}(x^{H2}_{h2s} + EU^{H2}_{h2s})$$

$$+ \sum_{\Gamma(p-MOW \leq pp \leq p,rp,k)} (-p^{H2}_{rp,k,h2s} W^K_k / \eta^{DIS}_{h2s} + cs^{H2}_{rp,k,h2s} W^K_k \eta^{CH}_{h2s}) \quad \forall p, h2s \tag{14c}$$

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

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

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

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

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