Electronic Companion for Risk-Averse Multi-Stage Stochastic CCUS-ED

EC.1 Problem Formulation

EC.1.1 Objective Function

The overall operating costs $f_t(\boldsymbol{x}_t, \boldsymbol{y}_t)$ at each stage t comprise generation cost, the nodal imbalance penalty, and the carbon-emission-related costs, as shown in (EC.1). In the final stage $t = T$, the objective function additionally incorporates an imbalance penalty to ensure the storage levels of rich and lean solvent tanks return to their initial values. In (EC.1), τ represents the time duration of each stage; $\mathcal{G}$ and $\mathcal{B}$ represent the sets of generation units and buses in the transmission network, respectively; C_g^{G} and C^{C} denote the generation cost and carbon tax, corresponding to the gross generation output $P_{g,t}^{\mathrm{G}}$ and net emissions $E_{g,t}^{\mathrm{N}}$, where carbon-emission-related costs might arise from various emission-related policy alternatives, such as carbon tax and carbon cap-and-trade; C^{P} indicates the penalty coefficient; $\delta_{b,t}^{+}$ and $\delta_{b,t}^{-}$ represent nodal energy deficiency and energy surplus, respectively; $E_{g,t}^{\mathrm{R},\pm}$ and $E_{g,t}^{\mathrm{L},\pm}$ respectively represent the positive and negative imbalance values in rich and lean solvent tanks at T, which are enforced in the final-stage constraint (EC.6).

$$
\begin{aligned}
f_t(\boldsymbol{x}_t, \boldsymbol{y}_t) =& \sum_{g\in\mathcal{G}} \left[C_g^{\mathrm{G}} \cdot P_{g,t}^{\mathrm{G}} + C^{\mathrm{C}} \cdot E_{g,t}^{\mathrm{N}}\right] \cdot \tau + \sum_{b\in\mathcal{B}} C^{\mathrm{P}} \cdot \left[\delta_{b,t}^{+} + \delta_{b,t}^{-}\right] \cdot \tau \\
&+ \begin{cases} \sum_{g\in\mathcal{G}} C^{\mathrm{P}} \cdot \left[E_{g,t}^{\mathrm{R}+} + E_{g,t}^{\mathrm{R}-} + E_{g,t}^{\mathrm{L}+} + E_{g,t}^{\mathrm{L}-}\right], & \text{if } t = T \\ 0 & \text{, otherwise} \end{cases}
\end{aligned} \tag{EC.1}
$$

EC.1.2 Constraints

Prevailing constraints including power balance requirements, power flow limits, power output constraints, and capacity constraints of the solvent tanks are detailed as follows.

EC.1.2.1 Nodal Power Balance Constraints

$$
\sum_{g\in\mathcal{G}_b} P_{g,t}^{\mathrm{N}} + \sum_{l\in to(b)} P_{l,t}^{\mathrm{L}} - \sum_{l\in fr(b)} P_{l,t}^{\mathrm{L}} + \delta_{b,t}^{+} - \delta_{b,t}^{-} = D_{b,t} \quad \forall b,\, t \tag{EC.2}
$$

where $\mathcal{G}_b \subseteq \mathcal{G}$, $fr(b) \subseteq \mathcal{L}$, and $to(b) \subseteq \mathcal{L}$ are the set of units connected to b, the set of lines that flow out of and into bus $b \in \mathcal{B}$, respectively; $D_{b,t}$ represents the net load at bus b.

EC.1.2.2 Power Flow Constraints

$$
-\overline{P}_l^{\mathrm{L}} \le P_{l,t}^{\mathrm{L}} \le \overline{P}_l^{\mathrm{L}} \qquad \forall l,\, t \tag{EC.3a}
$$

$$
P_{l,t}^{\mathrm{L}} = \frac{1}{X_l}\left(\theta_{fr(l),t} - \theta_{to(l),t}\right) \quad \forall l,\, t \tag{EC.3b}
$$

where $\overline{P}_l^{\mathrm{L}}$ denotes the power flow limit of transmission line $l \in \mathcal{L}$; X_l represents the reactance of line l; $\theta_{b,t}$ is the phase angle of bus $b \in \mathcal{B}$; $fr(l)$ and $to(l) \in \mathcal{B}$ return the starting and ending buses of line l.

EC.1.2.3 Power Output Constraints

$$
\begin{aligned}
&\underline{P}_g^{\mathrm{G}} \cdot \hat{u}_{g,t} \leq P_{g,t}^{\mathrm{G}} \leq \overline{P}_g^{\mathrm{G}} \cdot \hat{u}_{g,t} && \forall g,\, t && \text{(EC.4a)}\\
&P_{g,t}^{\mathrm{G}} - P_{g,t-1}^{\mathrm{G}} \leq RU_g \cdot \hat{u}_{g,t-1} + SU_g \cdot (\hat{u}_{g,t} - \hat{u}_{g,t-1}) && \forall g,\, t && \text{(EC.4b)}\\
&P_{g,t-1}^{\mathrm{G}} - P_{g,t}^{\mathrm{G}} \leq RD_g \cdot \hat{u}_{g,t} + SD_g \cdot (\hat{u}_{g,t-1} - \hat{u}_{g,t}) && \forall g,\, t && \text{(EC.4c)}\\
&P_{g,t}^{\mathrm{G}} = P_{g,t}^{\mathrm{N}} + \kappa_g^{\mathrm{F}} \cdot \overline{P}_g^{\mathrm{G}} \cdot \hat{u}_{g,t} + P_{g,t}^{\mathrm{C}} + \omega_g^{\mathrm{I}} \cdot E_{g,t}^{\mathrm{I}} && \forall g,\, t && \text{(EC.4d)}\\
&E_{g,t}^{\mathrm{N}} = E_{g,t}^{\mathrm{G}} - E_{g,t}^{\mathrm{C}} = e_g^{\mathrm{E}} \cdot P_{g,t}^{\mathrm{G}} - P_{g,t}^{\mathrm{C}} / \omega_g^{\mathrm{C}} && \forall g,\, t && \text{(EC.4e)}
\end{aligned}
$$

Constraints (EC.4a)-(EC.4c) enforce limitations on the gross power output of the CCUS power plants based on their operational and ramping limits, while taking commitment decisions $\hat{u}_{g,t}$ from the day-ahead UC as parameters. RU_g, RD_g, SU_g, and SD_g represent the upward, downward, startup, and shutdown ramping capacities of CCUS unit g, respectively. $\overline{P}_g^{\mathrm{G}}$ and $\underline{P}_g^{\mathrm{G}}$ denote maximum and minimum generation limits, respectively.

As depicted in Fig. 1, constraint (EC.4d) specifies the power balance of the gross power output P_{gt}^{G} of the power plant integrated with CCUS. P_{gt}^{G} consists of several components, including: (i) the net power P_{gt}^{C} which is the actual electric energy delivered to the power grids of the plant; (ii) the fixed power consumption which is proportional to the fixed carbon capture energy coefficient κ_g^{F}; (iii) the energy consumption P_{gt}^{C} which is associated with CO_2 absorption; and (iv) the desorption energy P_{gt}^{I} which is proportional to the absorbed emissions E_{gt}^{I} with coefficient ω_g^{I}.

Constraint (EC.4e) defines the net emission balance for each CCUS unit, where the gross emission E_{gt}^{G} is proportional to the gross power output, with e_g^{E} representing the CO_2 emission intensity factor. The captured emission E_{gt}^{C} is proportional to the absorption-related power consumption P_{gt}^{G}, with ω_g^{C} denoting the energy penalty coefficient.

EC.1.2.4 Capacity Constraints of the Solvent Tanks

$$
\begin{aligned}
&E_{g,t}^{\mathrm{R}} = E_{g,t-1}^{\mathrm{R}} + \left(E_{g,t}^{\mathrm{I}} - E_{g,t}^{\mathrm{C}}\right) \cdot \tau && \forall g,\, t && \text{(EC.5a)}\\
&E_{g,t}^{\mathrm{L}} = E_{g,t-1}^{\mathrm{L}} + \left(E_{g,t}^{\mathrm{C}} - E_{g,t}^{\mathrm{I}}\right) \cdot \tau && \forall g,\, t && \text{(EC.5b)}\\
&0 \leq E_{g,t}^{\mathrm{R}},\, E_{g,t}^{\mathrm{L}} \leq e_g^{\mathrm{E}} \cdot \overline{P}_g^{\mathrm{G}} \cdot T_g^{\mathrm{S}} && \forall g,\, t && \text{(EC.5c)}\\
&0 \leq E_{gt}^{\mathrm{I}},\, E_{g,t}^{\mathrm{C}} \leq \alpha_g^{\mathrm{C}} \cdot E_{g,t}^{\mathrm{N}} && \forall g,\, t && \text{(EC.5d)}
\end{aligned}
$$

where (EC.5a) indicates that the net flows of rich solvent $E_{g,t}^{\mathrm{R}} - E_{g,t-1}^{\mathrm{R}}$, pumped into the rich solvent storage tank from the absorber at stage t, could be expressed as the amount of rich solvent (in the form of contained CO_2) transferred from the absorber to the rich solvent tank $E_{g,t}^{\mathrm{I}}$ minus that drained from the rich solvent tank to the stripper $E_{g,t}^{\mathrm{C}}$. This expression can also be implemented for the net flow of the lean solvent $E_{g,t}^{\mathrm{L}} - E_{g,t-1}^{\mathrm{L}}$ drained from the lean solvent storage tank, as shown in (EC.5b). T_g^{S} is introduced in constraints (EC.5c) to describe the maximum capacity of the tanks, which is defined as the number of hours required to completely fill an empty rich/lean solvent tank under the condition $P_{g,t}^{\mathrm{G}} = \overline{P}_g^{\mathrm{G}}$. Constraint (EC.5d) indicates that the stripped amount E_{gt}^{C} and the absorbed amount E_{gt}^{I} depend on the maximum capturable emission, where α_g^{C} denotes the capture rate of CO_2 in the absorber.

Moreover, the final reservoir storage volumes in the final stage $t = T$ should return to their initial values. This is achieved by penalizing the gaps between the final stage storage levels and the initial stage values as evaluated in (EC.6).

$$
\begin{aligned}
&E_{g,T}^{\mathrm{R}} + E_{g,T}^{\mathrm{R}+} - E_{g,T}^{\mathrm{R}-} = E_{g,1}^{\mathrm{R}} = \beta_g^{\mathrm{R}} \cdot e_g^{\mathrm{E}} \cdot \overline{P}_g^{\mathrm{G}} \cdot T_g^{\mathrm{S}} && \forall g && \text{(EC.6a)}\\
&E_{g,T}^{\mathrm{L}} + E_{g,T}^{\mathrm{L}+} - E_{g,T}^{\mathrm{L}-} = E_{g,1}^{\mathrm{L}} = \beta_g^{\mathrm{L}} \cdot e_g^{\mathrm{E}} \cdot \overline{P}_g^{\mathrm{G}} \cdot T_g^{\mathrm{S}} && \forall g && \text{(EC.6b)}
\end{aligned}
$$

where β_g^{R} and β_g^{L} indicate the initial volumes of solvent in the rich and lean solvent storage tanks.