Appendix

A. Tractable Reformulation of the Multi-Stage Chance-Constrained Investment Problem (4)

Using uncertainty model (2), linear decision rules (5), and following the derivations in Section III, the multi-stage chance-constrained investment problem (4) takes the following second-order cone programming form:

$$\begin{aligned}\min_{\overline{\mathcal{V}}}\quad & \sum_{t=1}^{T}\Big(\mathrm{Tr}[S_t\widehat{\Sigma}S_t(Q_t^{\mathrm{g}\top}\overline{Y}_t+Q_t^{\mathrm{s}\top}\overline{\Theta}_t+Q_t^{\mathrm{p}\top}\overline{\Phi}_t)]+o_t^{\mathrm{e}\top}\overline{P}_tS_t\mathbb{1}+\sum_{\tau=1}^{t}\Big(o_t^{\mathrm{c}\top}\overline{Y}_\tau+o_t^{\mathrm{s}\top}\overline{\Theta}_\tau+o_t^{\mathrm{c}\top}\overline{\Phi}_\tau\Big)S_\tau\mathbb{1}\\ &\qquad+\sum_{w=1}^{W}\omega_w\sum_{h=1}^{H}\mathrm{Tr}[S_t\widehat{\Sigma}S_t(C_t^{\mathrm{e}}P_{twh}+C_t^{\mathrm{c}}Y_{twh})]\Big) \end{aligned}\tag{15a}$$

$$\text{s.t.}\quad \mathbb{1}^\top\big(P_{twh}+Y_{twh}+\Phi^{+}_{twh}-k^{\ell}_{twh}\circ L_t-\Phi^{-}_{twh}\big)=\mathbb{0},\tag{15b}$$

$$\Theta_{twh}-\Theta_{tw(h-1)}-\Phi^{+}_{twh}\eta^{+}+\Phi^{-}_{twh}/\eta^{-}=\mathbb{0},\tag{15c}$$

$$\left.\begin{aligned}&\left\|\begin{bmatrix}\overline{\Sigma}\,\big[F(P_{twh}+Y_{twh}+\Phi^{-}_{twh}-k^{\ell}_{twh}\circ L_t-\Phi^{+}_{twh})S_t\big]_e^\top\\ z^{\overline{f}}_{twhe}\end{bmatrix}\right\|\leqslant\sqrt{\overline{\varepsilon}^{\mathrm{f}}}\left(\overline{f}_e-x^{\overline{f}}_{twhe}\right),\\ &\big|\big[F(P_{twh}+Y_{twh}+\Phi^{-}_{twh}-k^{\ell}_{twh}\circ L_t-\Phi^{+}_{twh})S_t\big]_e\mathbb{1}\big|\leqslant z^{\overline{f}}_{twhe}+x^{\overline{f}}_{twhe},\\ &\overline{f}_e\geqslant x^{\overline{f}}_{twhe}\geqslant 0,z^{\overline{f}}_{twhe}\geqslant 0\end{aligned}\right\}\forall e\in[\![E]\!],\tag{15d}$$

$$\left.\begin{aligned}&\left\|\begin{bmatrix}\overline{\Sigma}\,[P_{twh}S_t]_i^\top\\ z^{\overline{p}}_{twhi}\end{bmatrix}\right\|\leqslant\sqrt{\overline{\varepsilon}^{\mathrm{g}}}\left(\tfrac{1}{2}k^{\mathrm{e}}_{twhi}\overline{p}_{ti}-x^{\overline{p}}_{twhi}\right),\\ &\big|[P_{twh}S_t]_i\mathbb{1}-\tfrac{1}{2}k^{\mathrm{e}}_{twhi}\overline{p}_{ti}\big|\leqslant z^{\overline{p}}_{twhi}+x^{\overline{p}}_{twhi},\\ &\tfrac{1}{2}k^{\mathrm{e}}_{twhi}\overline{p}_{ti}\geqslant x^{\overline{p}}_{twhi}\geqslant 0,z^{\overline{p}}_{twhi}\geqslant 0\end{aligned}\right\}\forall i\in[\![N]\!],\tag{15e}$$

$$\left.\begin{aligned}&\left\|\overline{\Sigma}\left[k^{\mathrm{e}}_{twhi}\circ\textstyle\sum_{\tau=1}^{t}\overline{Y}_\tau S_\tau-Y_{twh}S_t\right]_i^\top\right\|\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{g}})/\overline{\varepsilon}^{\mathrm{g}}}}\left[k^{\mathrm{e}}_{twhi}\circ\textstyle\sum_{\tau=1}^{t}\overline{Y}_\tau S_\tau-Y_{twh}S_t\right]_i\mathbb{1},\\ &\left\|\overline{\Sigma}\,[Y_{twh}S_t]_i^\top\right\|\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{g}})/\overline{\varepsilon}^{\mathrm{g}}}}\,[Y_{twh}S_t]_i\,\mathbb{1}\end{aligned}\right\}\forall i\in[\![N]\!],\tag{15f}$$

$$\left.\begin{aligned}&\left\|\begin{bmatrix}\overline{\Sigma}\,\big[\big(P_{twh}-P_{tw(h-1)}\big)S_t\big]_i^\top\\ z^{r^{\mathrm{e}}}_{twhi}\end{bmatrix}\right\|\leqslant\sqrt{\overline{\varepsilon}^{\mathrm{r}}}\,\tfrac{1}{2}(r_i^{\mathrm{e+}}+r_i^{\mathrm{e-}})\overline{p}_{ti}-x^{r^{\mathrm{e}}}_{twhi},\\ &\big|\big[\big(P_{twh}-P_{tw(h-1)}\big)S_t\big]_i\mathbb{1}-\tfrac{1}{2}(r_i^{\mathrm{e+}}+r_i^{\mathrm{e-}})\overline{p}_{ti}\big|\leqslant z^{r^{\mathrm{e}}}_{twhi}+x^{r^{\mathrm{e}}}_{twhi}\\ &\tfrac{1}{2}(r_i^{\mathrm{e+}}+r_i^{\mathrm{e-}})\overline{p}_{ti}\geqslant x^{r^{\mathrm{e}}}_{twhi}\geqslant 0,z^{r^{\mathrm{e}}}_{twhi}\geqslant 0,\end{aligned}\right\}\forall i\in[\![N]\!],\tag{15g}$$

$$\left.\begin{aligned}&\left\|\overline{\Sigma}\left[r^{\mathrm{c-}}\circ\textstyle\sum_{\tau=1}^{t}\overline{Y}_\tau S_\tau+Y_{twh}S_t-Y_{tw(h-1)}S_t\right]_i^\top\right\|\\ &\quad\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{g}})/\overline{\varepsilon}^{\mathrm{r}}}}\left[r^{\mathrm{c-}}\circ\textstyle\sum_{\tau=1}^{t}\overline{Y}_\tau S_\tau+Y_{twh}S_t-Y_{tw(h-1)}S_t\right]_i\mathbb{1},\\ &\left\|\overline{\Sigma}\left[r^{\mathrm{c+}}\circ\textstyle\sum_{\tau=1}^{t}\overline{Y}_\tau S_\tau-Y_{twh}S_t+Y_{tw(h-1)}S_t\right]_i^\top\right\|\\ &\quad\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{g}})/\overline{\varepsilon}^{\mathrm{r}}}}\left[r^{\mathrm{c+}}\circ\textstyle\sum_{\tau=1}^{t}\overline{Y}_\tau S_\tau-Y_{twh}S_t+Y_{tw(h-1)}S_t\right]_i\mathbb{1},\end{aligned}\right\}\forall i\in[\![N]\!],\tag{15h}$$

$$\left.\begin{aligned}&\left\|\overline{\Sigma}\left[\textstyle\sum_{\tau=1}^{t}\overline{\Theta}_{\tau wh}S_\tau-\Theta_{twh}S_t\right]_i^\top\right\|\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{s}})/\overline{\varepsilon}^{\mathrm{s}}}}\left[\textstyle\sum_{\tau=1}^{t}\overline{\Theta}_{\tau wh}S_\tau-\Theta_{twh}S_t\right]_i\mathbb{1},\\ &\left\|\overline{\Sigma}\,[\Theta_{twh}S_t]_i^\top\right\|\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{s}})/\overline{\varepsilon}^{\mathrm{s}}}}\,[\Theta_{twh}S_t]_i\,\mathbb{1},\\ &\left\|\overline{\Sigma}\left[\textstyle\sum_{\tau=1}^{t}\overline{\Phi}_{\tau wh}S_\tau-\Phi^{+}_{twh}S_t\right]_i^\top\right\|\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{s}})/\overline{\varepsilon}^{\mathrm{s}}}}\left[\textstyle\sum_{\tau=1}^{t}\overline{\Phi}_{\tau wh}S_\tau-\Phi^{+}_{twh}S_t\right]_i\mathbb{1},\\ &\left\|\overline{\Sigma}\,[\Phi^{+}_{twh}S_t]_i^\top\right\|\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{s}})/\overline{\varepsilon}^{\mathrm{s}}}}\,[\Phi^{+}_{twh}S_t]_i\,\mathbb{1},\\ &\left\|\overline{\Sigma}\left[\textstyle\sum_{\tau=1}^{t}\overline{\Phi}_{\tau wh}S_\tau-\Phi^{-}_{twh}S_t\right]_i^\top\right\|\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{s}})/\overline{\varepsilon}^{\mathrm{s}}}}\left[\textstyle\sum_{\tau=1}^{t}\overline{\Phi}_{\tau wh}S_\tau-\Phi^{-}_{twh}S_t\right]_i\mathbb{1},\\ &\left\|\overline{\Sigma}\,[\Phi^{-}_{twh}S_t]_i^\top\right\|\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{s}})/\overline{\varepsilon}^{\mathrm{s}}}}\,[\Phi^{-}_{twh}S_t]_i\,\mathbb{1},\\ &\left\|\overline{\Sigma}\left[\textstyle\sum_{\tau=1}^{t}\overline{\Phi}_{\tau wh}S_\tau-(\Phi^{+}_{twh}+\Phi^{-}_{twh})S_t\right]_i^\top\right\|\leqslant\tfrac{1}{\sqrt{(1-\overline{\varepsilon}^{\mathrm{s}})/\overline{\varepsilon}^{\mathrm{s}}}}\left[\textstyle\sum_{\tau=1}^{t}\overline{\Phi}_{\tau wh}S_\tau-(\Phi^{+}_{twh}+\Phi^{-}_{twh})S_t\right]_i\mathbb{1}\end{aligned}\right\}\forall i\in[\![N]\!],\tag{15i}$$

in variables $\overline{\mathcal{V}} = \{\overline{Y}, \overline{\Theta}, \overline{\Phi}, P, Y, \Theta, \Phi^{\odot}, z^{\odot}, x^{\odot}\}$, plus emission and investment limits as in (4g) and (4h), respectively. Here, the double-sided entries in power flow constraint (4c) are reformulated into (15d) with $\overline{\varepsilon}^{\mathrm{f}} = \varepsilon^{\mathrm{f}}/E$. The double-sided existing generation limits in (4d) are reformulated into (15e), and single-sided candidate generation limits in (4d) are reformulated into (15f), while fixing $\overline{\varepsilon}^{\mathrm{g}} = \varepsilon^{\mathrm{g}}/(3N)$. Similarly, the double-sided ramping limits on existing generation in (4e) are reformulated into (15g) and the single-sided ramping limits on candidate generation in (4e) are reformulated into (15h). Here, we set $\overline{\varepsilon}^{\mathrm{r}} = \varepsilon^{\mathrm{r}}/(3N)$. All entries in the operational storage constraint (4f) are single-sided and reformulated into (15i) with $\overline{\varepsilon}^{\mathrm{s}} = \varepsilon^{\mathrm{s}}/(7N)$.

B. The Dual Stochastic Problem Formulation

The dual problem of the chance-constrained program (4) takes the following form:

$$
\begin{aligned}
\max_{\lambda}\quad & \mathbb{E}\Bigg[\sum_{t=1}^{T}\Bigg[\sum_{w=1}^{W}\Bigg\langle\sum_{h=1}^{H}\Bigg(\mathbb{1}^{\top}M_{\ell}\mathrm{diag}\left[k_{twh}^{\ell}\right]\ell_t(\boldsymbol{\xi}^t)\lambda_{twh}^{b}(\boldsymbol{\xi}^t) - \left(FM_{\ell}\mathrm{diag}\left[k_{twh}^{\ell}\right]\ell_t(\boldsymbol{\xi}^t)+\overline{f}\right)^{\top}\lambda_{twh}^{\overline{f}}(\boldsymbol{\xi}^t)\\
&\qquad + \left(FM_{\ell}\mathrm{diag}\left[k_{twh}^{\ell}\right]\ell_t(\boldsymbol{\xi}^t)-\overline{f}\right)^{\top}\lambda_{twh}^{\underline{f}}(\boldsymbol{\xi}^t) - \left(\mathrm{diag}\left[k_{twh}^{\mathrm{e}}\right]\overline{p}_t\right)^{\top}\lambda_{twh}^{p}(\boldsymbol{\xi}^t)\Bigg)\Bigg\rangle\\
&\qquad - \overline{e}_t(\boldsymbol{\xi}^t)\lambda_t^{e}(\boldsymbol{\xi}^t) - \overline{y}_t^{\max\top}\lambda_t^{\overline{y}}(\boldsymbol{\xi}^t) - \overline{\varphi}_t^{\max\top}\lambda_t^{\overline{\varphi}}(\boldsymbol{\xi}^t) - \overline{\vartheta}_t^{\max\top}\lambda_t^{\overline{\vartheta}}(\boldsymbol{\xi}^t)\Bigg]\\
&- \sum_{t=1}^{T}\sum_{w=1}^{W}\sum_{h=2}^{H}\Big(\left(\mathrm{diag}\left[r^{\mathrm{e-}}\right]\overline{p}_t\right)^{\top}\lambda_{twh}^{r^{\mathrm{e-}}}(\boldsymbol{\xi}^t) + \left(\mathrm{diag}\left[r^{\mathrm{e+}}\right]\overline{p}_t\right)^{\top}\lambda_{twh}^{r^{\mathrm{e+}}}(\boldsymbol{\xi}^t)\Big)\Bigg] && \text{(16a)}\\
\text{s.t.}\quad & \mathbb{P}\left[\begin{aligned}&q_t^{\mathrm{g}}(\boldsymbol{\xi}^t)+\sum_{\tau=t}^{T}o_{\tau}^{\mathrm{g}} \leqslant \sum_{\tau=t}^{T}\sum_{w=1}^{W}\Bigg(\sum_{h=1}^{H}\mathrm{diag}\left[k_{twh}^{\mathrm{c}}\right]^{\top}\lambda_{\tau wh}^{y}(\boldsymbol{\xi}^{\tau})\\ &\qquad + \sum_{h=2}^{H}\left(\mathrm{diag}\left[r^{\mathrm{c-}}\right]^{\top}\lambda_{\tau wh}^{r^{\mathrm{c-}}}(\boldsymbol{\xi}^{\tau}) + \mathrm{diag}\left[r^{\mathrm{c+}}\right]^{\top}\lambda_{\tau wh}^{r^{\mathrm{c+}}}(\boldsymbol{\xi}^{\tau})\right)\Bigg) - \lambda_t^{\overline{y}}(\boldsymbol{\xi}^t)\end{aligned}\right] \geqslant 1-\varepsilon^{\overline{y}}\\
& \mathbb{P}\left[q_t^{\mathrm{s}}(\boldsymbol{\xi}^t)+\sum_{\tau=t}^{T}o_{\tau}^{\mathrm{s}} \leqslant \sum_{\tau=t}^{T}\sum_{w=1}^{W}\sum_{h=1}^{H}\lambda_{\tau wh}^{\vartheta}(\boldsymbol{\xi}^{\tau}) - \lambda_t^{\overline{\vartheta}}(\boldsymbol{\xi}^t)\right] \geqslant 1-\varepsilon^{\overline{\vartheta}} && \text{(16b)}\\
& \mathbb{P}\left[q_t^{\mathrm{p}}(\boldsymbol{\xi}^t)+\sum_{\tau=t}^{T}o_{\tau}^{\mathrm{p}} \leqslant \sum_{\tau=t}^{T}\sum_{w=1}^{W}\sum_{h=1}^{H}\left(\lambda_{\tau wh}^{\varphi^{+}}(\boldsymbol{\xi}^{\tau})+\lambda_{\tau wh}^{\varphi^{-}}(\boldsymbol{\xi}^{\tau})+\lambda_{\tau wh}^{\varphi}(\boldsymbol{\xi}^{\tau})\right) - \lambda_t^{\overline{\vartheta}}(\boldsymbol{\xi}^t)\right] \geqslant 1-\varepsilon^{\varphi} && \text{(16c)}\\
& \mathbb{P}\left[\begin{aligned}&\omega_w c_t^{\mathrm{e}}(\boldsymbol{\xi}^t) \leqslant \lambda_{twh}^{b}(\boldsymbol{\xi}^t)(\mathbb{1}^{\top}M_p)^{\top} + (FM_p)^{\top}\left(\lambda_{twh}^{\underline{f}}(\boldsymbol{\xi}^t)-\lambda_{twh}^{\overline{f}}(\boldsymbol{\xi}^t)\right) - \lambda_{twh}^{p}(\boldsymbol{\xi}^t)\\ &\qquad + \underbrace{\lambda_{twh}^{r^{\mathrm{e-}}}(\boldsymbol{\xi}^t)-\lambda_{twh}^{r^{\mathrm{e+}}}(\boldsymbol{\xi}^t)}_{h\geqslant 2} + \underbrace{\lambda_{tw(h+1)}^{r^{\mathrm{e+}}}(\boldsymbol{\xi}^t)-\lambda_{tw(h+1)}^{r^{\mathrm{e-}}}(\boldsymbol{\xi}^t)}_{h<H} - \omega_w\lambda_t^{e}(\boldsymbol{\xi}^t)e^{\mathrm{e}}\end{aligned}\right] \geqslant 1-\varepsilon^{p}\\
& \mathbb{P}\left[\begin{aligned}&\omega_w c_t^{\mathrm{c}}(\boldsymbol{\xi}^t) \leqslant \lambda_{twh}^{b}(\boldsymbol{\xi}^t)(\mathbb{1}^{\top}M_y)^{\top} + (FM_y)^{\top}\left(\lambda_{twh}^{\underline{f}}(\boldsymbol{\xi}^t)-\lambda_{twh}^{\overline{f}}(\boldsymbol{\xi}^t)\right) - \lambda_{twh}^{y}(\boldsymbol{\xi}^t)\\ &\qquad + \underbrace{\lambda_{twh}^{r^{\mathrm{c-}}}(\boldsymbol{\xi}^t)-\lambda_{twh}^{r^{\mathrm{c+}}}(\boldsymbol{\xi}^t)}_{h\geqslant 2} + \underbrace{\lambda_{tw(h+1)}^{r^{\mathrm{c+}}}(\boldsymbol{\xi}^t)-\lambda_{tw(h+1)}^{r^{\mathrm{c-}}}(\boldsymbol{\xi}^t)}_{h<H} - \omega_w\lambda_t^{e}(\boldsymbol{\xi}^t)e^{\mathrm{c}}\end{aligned}\right] \geqslant 1-\varepsilon^{y} && \text{(16d)}\\
& \mathbb{P}\left[\begin{aligned}&\mathbb{0} \leqslant \lambda_{twh}^{b}(\boldsymbol{\xi}^t)(\mathbb{1}^{\top}M_s)^{\top} + (FM_s)^{\top}\left(\lambda_{twh}^{\underline{f}}(\boldsymbol{\xi}^t)-\lambda_{twh}^{\overline{f}}(\boldsymbol{\xi}^t)\right)\\ &\quad \underbrace{+\lambda_{twh}^{s}(\boldsymbol{\xi}^t)\tfrac{1}{\eta^{-}}}_{h\geqslant 2}\underbrace{+\lambda_{tw}^{s1}(\boldsymbol{\xi}^t)\tfrac{1}{\eta^{-}}}_{h=1} - \lambda_{twh}^{\varphi^{-}}(\boldsymbol{\xi}^t) - \lambda_{twh}^{\varphi}(\boldsymbol{\xi}^t)\end{aligned}\right] \geqslant 1-\varepsilon^{\varphi^{-}} && \text{(16e)}\\
& \mathbb{P}\left[\begin{aligned}&\mathbb{0} \geqslant \lambda_{twh}^{b}(\boldsymbol{\xi}^t)(\mathbb{1}^{\top}M_s)^{\top} + (FM_s)^{\top}\left(\lambda_{twh}^{\underline{f}}(\boldsymbol{\xi}^t)-\lambda_{twh}^{\overline{f}}(\boldsymbol{\xi}^t)\right)\\ &\quad \underbrace{+\lambda_{twh}^{s}(\boldsymbol{\xi}^t)\eta^{+}}_{h\geqslant 2}\underbrace{+\lambda_{tw}^{s1}(\boldsymbol{\xi}^t)\eta^{+}}_{h=1} + \lambda_{twh}^{\varphi^{+}}(\boldsymbol{\xi}^t) + \lambda_{twh}^{\varphi}(\boldsymbol{\xi}^t)\end{aligned}\right] \geqslant 1-\varepsilon^{\varphi^{+}} && \text{(16f)}\\
& \mathbb{P}\left[\mathbb{0} \leqslant \underbrace{\lambda_{tw}^{s1}(\boldsymbol{\xi}^t)}_{h=1}\underbrace{+\lambda_{twh}^{s}(\boldsymbol{\xi}^t)}_{h\geqslant 2}\underbrace{-\lambda_{tw(h+1)}^{s}(\boldsymbol{\xi}^t)}_{h<H} - \lambda_{twh}^{\vartheta}(\boldsymbol{\xi}^t)\right] \geqslant 1-\varepsilon^{\vartheta} && \text{(16g)}\\
& \forall\mathbb{P}\in\mathcal{P},\ \forall t\in[\![T]\!],\ \forall w\in[\![W]\!],\ \forall h\in[\![H]\!],
\end{aligned}
$$

where the optimization variables are denoted by the Greek letter λ. Here, the expected value of the dual objective function is maximized subject to the series of joint chance constraints, where the subscript $\odot$ in $\varepsilon^{\odot}$ denotes the primal variables to which the dual constraints correspond. Note, that the tractable second-order cone programming form of problem (16) is achieved similarly to problem (15) and omitted in the interest of space.