Available online at: https://github.com/alherm/TSO-DSO_coordination

This online companion includes four appendixes. Appendix A provides the mathematical formulation of the lower-level problem for DSO market, and then its corresponding Karush–Kuhn–Tucker (KKT) conditions are presented. Appendixes B and C provide the KKT conditions of the lower-level problems representing the day-ahead and real-time markets, respectively. Finally, Appendix D explains why the KKT conditions of the DSO market-clearing problem in Appendix A are redundant, proving this problem can be removed.

Appendix A. Lower-Level Problem Representing the DSO Market

Each distribution system operator (DSO) e clears a local market to pre-qualify the participation of flexible resources located in its operational domain in the wholesale day-ahead market. If necessary, the DSO imposes caps on the quantity bids of DSO-level flexible resources to the day-ahead market. The DSO market-clearing problem includes both day-ahead and real-time stages. Recall that, aligned with European market design, the network constraints in the day-ahead stage are not included. However, such constraints are enforced in the real-time stage using a conic relaxation of power flow equations in the distribution level. The resulting model is a stochastic second-order cone programming (SOCP) problem as below. Note that dual variables are provided alongside each constraint:

$$\begin{aligned}\max_{\Xi^{\mathrm{E}}} \quad \mathcal{SW}_e = & \sum_{d\in D_e^{\mathrm{D}}} \pi_d^{\mathrm{DA}} \widetilde{p}_d^{\mathrm{DA}} - \sum_{g\in G_e^{\mathrm{D}}} \pi_g^{\mathrm{DA}} \widetilde{p}_g^{\mathrm{DA}} - VOLL\ s_e^{\mathrm{DA}} - \sum_{r\in R_e^{\mathrm{D}}} \pi^{\mathrm{R}} w_r^{\mathrm{DA}} - \pi_e^{\mathrm{IO,DA}} p_e^{\mathrm{IO,DA}} \\ & - \sum_{\omega} \phi_\omega \Bigg[\sum_{g\in G_e^{\mathrm{D}}} \Big(\pi_g^{\mathrm{DA}} (p_{g\omega}^{\mathrm{RT}} - \widetilde{p}_g^{\mathrm{DA}}) + \pi_g^{\uparrow} p_{g\omega}^{\uparrow} + \pi_g^{\downarrow} p_{g\omega}^{\downarrow} \Big) + \sum_{d\in D_e^{\mathrm{D}}} \Big(\pi_d^{\mathrm{DA}} (\widetilde{p}_d^{\mathrm{DA}} - p_{d\omega}^{\mathrm{RT}}) \\ & + \pi_d^{\uparrow} p_{d\omega}^{\uparrow} + \pi_d^{\downarrow} p_{d\omega}^{\downarrow} \Big) + \sum_{n\in N_e^{\mathrm{D}}} VOLL\ s_{n\omega}^{\mathrm{RT}} + \pi_e^{\mathrm{IO,DA}} (p_{e\omega}^{\mathrm{IO,RT}} - p_e^{\mathrm{IO,DA}}) \\ & + \pi_e^{\uparrow \mathrm{IO}} p_{e\omega}^{\uparrow \mathrm{IO}} + \pi_e^{\downarrow \mathrm{IO}} p_{e\omega}^{\downarrow \mathrm{IO}} + \sum_{r\in R_e^{\mathrm{D}}} \Big(\pi^{\mathrm{R}} (w_{r\omega}^{\mathrm{RT}} - w_r^{\mathrm{DA}}) + \pi^{\uparrow \mathrm{R}} w_{r\omega}^{\uparrow} + \pi^{\downarrow \mathrm{R}} w_{r\omega}^{\downarrow} \Big) \Bigg] \end{aligned} \tag{A.1a}$$

subject to:

Day-ahead constraints (deterministic and single-node):

$$\sum_{g\in G_e} \widetilde{p}_g^{\mathrm{DA}} - \sum_{d\in D_e^{\mathrm{D}}} \widetilde{p}_d^{\mathrm{DA}} + \sum_{r\in R_e^{\mathrm{D}}} w_r^{\mathrm{DA}} + s_e^{\mathrm{DA}} + p_e^{\mathrm{IO,DA}} = 0, \quad : (\lambda_e^{\mathrm{DA}}) \tag{A.1b}$$

$$\underline{P}_g \le \widetilde{p}_g^{\mathrm{DA}} \le \overline{P}_g, \quad \forall g \in G_e^{\mathrm{D}} \quad : (\varsigma_g^{\mathrm{DA}-}, \varsigma_g^{\mathrm{DA}+}) \tag{A.1c}$$

$$\underline{P}_d \le \widetilde{p}_d^{\mathrm{DA}} \le \overline{P}_d, \quad \forall d \in D_e^{\mathrm{D}} \quad : (\varsigma_d^{\mathrm{DA}-}, \varsigma_d^{\mathrm{DA}+}) \tag{A.1d}$$

$$0 \le w_r^{\mathrm{DA}} \le W_r^{\mathrm{DA}}, \ \forall r \in R_e^{\mathrm{D}} \quad : (\iota_r^{-}, \iota_r^{+}) \tag{A.1e}$$

$$\underline{f}_e \le p_e^{\mathrm{IO,DA}} \le \overline{f}_e, \quad : (\rho_e^{\mathrm{DA}-}, \rho_e^{\mathrm{DA}+}) \tag{A.1f}$$

$$0 \le s_e^{\mathrm{DA}} \le \sum_{d} p_d^{\mathrm{DA}}, \quad : (\Upsilon_e^{\mathrm{DA}-}, \Upsilon_e^{\mathrm{DA}+}) \tag{A.1g}$$

Real-time constraints (stochastic and network-aware):

$$p^{\mathrm{RT}}_{g\omega} = p^{\mathrm{DA}}_{g} + p^{\uparrow}_{g\omega} - p^{\downarrow}_{g\omega}, \quad \forall \omega, g \in G^{\mathrm{D}}_{e}, \quad : (\zeta^{\mathrm{p}}_{g\omega}) \tag{A.1h}$$

$$p^{\mathrm{RT}}_{d\omega} = p^{\mathrm{DA}}_{d} - p^{\uparrow}_{d\omega} + p^{\downarrow}_{d\omega}, \quad \forall \omega, d \in D^{\mathrm{D}}_{e}, \quad : (\zeta^{\mathrm{p}}_{d\omega}) \tag{A.1i}$$

$$w^{\mathrm{RT}}_{r\omega} = w^{\mathrm{DA}}_{r} + w^{\uparrow}_{r\omega} - w^{\downarrow}_{r\omega}, \ \forall \omega, r \in R^{\mathrm{D}}_{e}, \quad : (\zeta^{\mathrm{p}}_{r\omega}) \tag{A.1j}$$

$$\sum_{g\in G_n} p^{\mathrm{RT}}_{g\omega} - \sum_{d\in D_n} p^{\mathrm{RT}}_{d\omega} + \sum_{r\in R_n} w^{\mathrm{RT}}_{r\omega} + p^{\mathrm{IO,RT}}_{e\omega}|_{n=n^{\mathrm{LV}}_e} + s^{\mathrm{RT}}_{n\omega} = \sum_{l\in n\rightarrow} p^{\mathrm{RT}}_{l\omega} - \sum_{l\in \rightarrow n} p^{\mathrm{RT}}_{l\omega}, \ \forall \omega, n \in N^{\mathrm{D}}_{e} \ : (\lambda^{\mathrm{p,RT}}_{n\omega}) \tag{A.1k}$$

$$p^{\mathrm{IO,RT}}_{e\omega} = p^{\mathrm{IO,DA}}_{e} + p^{\uparrow\mathrm{IO}}_{e\omega} - p^{\downarrow\mathrm{IO}}_{e\omega}, \ \forall \omega, \ : (\zeta^{\mathrm{IO}}_{e\omega}) \tag{A.1l}$$

$$\sum_{g\in G_n} q^{\mathrm{RT}}_{g\omega} - \sum_{d\in D_n} q^{\mathrm{RT}}_{d\omega} + s^{\mathrm{q,RT}}_{n\omega} + q^{\mathrm{IO,RT}}_{e\omega}|_{n=n^{\mathrm{LV}}_e} = \sum_{l\in n\rightarrow} q^{\mathrm{RT}}_{l\omega} - \sum_{l\in \rightarrow n} q^{\mathrm{RT}}_{l\omega}, \ \forall \omega, n \in N^{\mathrm{D}}_{e} \ : (\lambda^{\mathrm{q,RT}}_{n\omega}) \tag{A.1m}$$

$$p^{\mathrm{RT}^2}_{l\omega} + q^{\mathrm{RT}^2}_{l\omega} \leq \varphi^{\mathrm{RT}}_{l\omega} v^{\mathrm{RT}}_{n\omega}, \quad \forall \omega, l \in L^{\mathrm{D}}_{e} \ : (\gamma_{l\omega}) \tag{A.1n}$$

$$p^{\mathrm{RT}}_{l\omega} + p^{\mathrm{RT}}_{l'\omega} = R_l \varphi^{\mathrm{RT}}_{l\omega}, \quad \forall \omega, l \in L^{\mathrm{D}}_{e} \ : (\mu^{\mathrm{p}}_{l\omega}) \tag{A.1o}$$

$$q^{\mathrm{RT}}_{l\omega} + q^{\mathrm{RT}}_{l'\omega} = X_l \varphi^{\mathrm{RT}}_{l\omega}, \quad \forall \omega, l \in L^{\mathrm{D}}_{e} \ : (\mu^{\mathrm{q}}_{l\omega}) \tag{A.1p}$$

$$p^{\mathrm{RT}^2}_{l\omega} + q^{\mathrm{RT}^2}_{l\omega} \leq S_l, \quad \forall \omega, l \in L^{\mathrm{D}}_{e} \ : (\eta_{l\omega}) \tag{A.1q}$$

$$v^{\mathrm{RT}}_{m\omega} = v^{\mathrm{RT}}_{n\omega} - 2(R_l p^{\mathrm{RT}}_{l\omega} + X_l q^{\mathrm{RT}}_{l\omega}) + (R_l^2 + X_l^2)\varphi^{\mathrm{RT}}_{l\omega}, \forall \omega, l \in L^{\mathrm{D}}_{e} \quad : (\beta_{l\omega}) \tag{A.1r}$$

$$\underline{V}^2_n \leq v^{\mathrm{RT}}_{n\omega} \leq \overline{V}^2_n, \quad \forall \omega, n \in N^{\mathrm{D}}_{e} \quad : (\sigma^{-}_{n\omega}, \sigma^{+}_{n\omega}) \tag{A.1s}$$

$$0 \leq w^{\mathrm{RT}}_{r\omega} \leq W^{\mathrm{RT}}_{r\omega}, \quad \forall \omega, n \in N_e \quad : (\nu^{-}_{n\omega}, \nu^{+}_{n\omega}) \tag{A.1t}$$

$$\underline{P}_g \leq p^{\mathrm{RT}}_{g\omega} \leq \overline{P}_g, \quad \forall \omega, g \in G_e \quad : (\varsigma^{\mathrm{RT}-}_{g\omega}, \varsigma^{\mathrm{RT}+}_{g\omega}) \tag{A.1u}$$

$$\underline{P}_d \leq p^{\mathrm{RT}}_{d\omega} \leq \overline{P}_d, \quad \forall \omega, d \in D_e \quad : (\varsigma^{\mathrm{RT}-}_{d\omega}, \varsigma^{\mathrm{RT}+}_{d\omega}) \tag{A.1v}$$

$$\underline{Q}_g \leq q^{\mathrm{RT}}_{g\omega} \leq \overline{Q}_g, \quad \forall \omega, g \in G_e \quad : (\kappa^{\mathrm{RT}-}_{g\omega}, \kappa^{\mathrm{RT}+}_{g\omega}) \tag{A.1w}$$

$$\underline{Q}_d \leq q^{\mathrm{RT}}_{d\omega} \leq \overline{Q}_d, \quad \forall \omega, d \in D_e \quad : (\kappa^{\mathrm{RT}-}_{d\omega}, \kappa^{\mathrm{RT}+}_{d\omega}) \tag{A.1x}$$

$$\underline{f}_e \leq p^{\mathrm{IO,RT}}_{e\omega} \leq \overline{f}_e, \quad \forall \omega \quad : (\rho^{\mathrm{RT}-}_{e\omega}, \rho^{\mathrm{RT}+}_{e\omega}) \tag{A.1y}$$

$$p^{\uparrow}_{g\omega} \geq 0, \ \forall \omega, g \ : (\epsilon^{\mathrm{p}\uparrow}_{g\omega}), \quad p^{\downarrow}_{g\omega} \geq 0, \ \forall \omega, g \ : (\epsilon^{\mathrm{p}\downarrow}_{g\omega}) \tag{A.1z}$$

$$p^{\uparrow}_{d\omega} \geq 0, \ \forall d, \omega \ : (\varepsilon^{\mathrm{p}\uparrow}_{d\omega}), \quad p^{\downarrow}_{d\omega} \geq 0, \ \forall d, \omega \ : (\varepsilon^{\mathrm{p}\downarrow}_{d\omega}) \tag{A.1aa}$$

$$p^{\uparrow\mathrm{IO}}_{e\omega} \geq 0, \ \forall \omega, \ : (\epsilon^{\uparrow\mathrm{IO}}_{e\omega}), \ p^{\downarrow\mathrm{IO}}_{e\omega} \geq 0, \ \forall \omega, \ : (\epsilon^{\downarrow\mathrm{IO}}_{e\omega}) \tag{A.1ab}$$

$$0 \leq s^{\mathrm{RT}}_{n\omega} \leq \sum_{d\in D_n} p^{\mathrm{RT}}_{d\omega}, \ \forall \omega, n \in N^{\mathrm{D}}_{e}, \ : (\Upsilon^{\mathrm{RT}-}_{n\omega}, \Upsilon^{\mathrm{RT}+}_{n\omega}) \tag{A.1ac}$$

$$w^{\uparrow}_{r\omega} \geq 0, \ \forall \omega, w \ : (\epsilon^{\mathrm{p}\uparrow}_{r\omega}), \quad w^{\downarrow}_{r\omega} \geq 0, \ \forall \omega, w \ : (\epsilon^{\mathrm{p}\downarrow}_{r\omega}), \tag{A.1ad}$$

where the set of primal variables is $\Xi^{\mathrm{E}} = \{\widetilde{p}^{\mathrm{DA}}_{g}, \widetilde{p}^{\mathrm{DA}}_{d}, p^{\mathrm{RT}}_{g\omega}, p^{\uparrow}_{g\omega}, p^{\downarrow}_{g\omega}, p^{\mathrm{RT}}_{d\omega}, p^{\uparrow}_{d\omega}, p^{\downarrow}_{d\omega}, q^{\mathrm{RT}}_{g\omega}, q^{\mathrm{RT}}_{d\omega}, s^{\mathrm{RT}}_{n\omega}, s^{\mathrm{DA}}_{e}, w^{\mathrm{RT}}_{n\omega}, p^{\mathrm{RT}}_{l\omega}, q^{\mathrm{RT}}_{l\omega}, \varphi^{\mathrm{RT}}_{l\omega}, v^{\mathrm{RT}}_{n\omega}, w^{\mathrm{DA}}_{e}, p^{\mathrm{IO,DA}}_{e}, p^{\mathrm{IO,RT}}_{e}, p^{\uparrow\mathrm{IO}}_{e}, p^{\downarrow\mathrm{IO}}_{e}, s^{\mathrm{q,RT}}_{n\omega}\}$. The KKT conditions of lower-level problem (A.1) are

$$(\mathrm{A.1b}), (\mathrm{A.1h}) - (\mathrm{A.1m}), (\mathrm{A.1o}), (\mathrm{A.1p}), (\mathrm{A.1r}) \tag{A.2a}$$

$$(\widetilde{p}_g^{\mathrm{DA}}):\ \pi_g^{\mathrm{DA}} - \sum_\omega \phi_\omega \pi_g^{\mathrm{DA}} - \lambda_e^{\mathrm{DA}} - \varsigma_g^{\mathrm{DA}-} + \varsigma_g^{\mathrm{DA}+} + \sum_\omega \zeta_{g\omega}^{\mathrm{p}} = 0, \quad \forall g \in G_e^{\mathrm{D}} \tag{A.2b}$$

$$(\widetilde{p}_d^{\mathrm{DA}}): \sum_\omega \left(\zeta_{d\omega}^{\mathrm{p}} + \phi_\omega \pi_d^{\mathrm{DA}}\right) - \pi_d^{\mathrm{DA}} + \lambda_e^{\mathrm{DA}} - \varsigma_d^{\mathrm{DA}-} + \varsigma_d^{\mathrm{DA}+} - \Upsilon_e^{\mathrm{DA}+} = 0, \quad \forall d \in D_e^{\mathrm{D}} \tag{A.2c}$$

$$(p_{g\omega}^{\uparrow}):\ \phi_\omega \pi_g^{\uparrow} + \zeta_{g\omega}^{\mathrm{p}} - \epsilon_{g\omega}^{\mathrm{p}\uparrow} = 0, \quad \forall \omega, g \in G_e^{\mathrm{D}} \tag{A.2d}$$

$$(p_{g\omega}^{\downarrow}):\ \phi_\omega \pi_g^{\downarrow} - \zeta_{g\omega}^{\mathrm{p}} - \epsilon_{g\omega}^{\mathrm{p}\downarrow} = 0, \quad \forall \omega, g \in G_e^{\mathrm{D}} \tag{A.2e}$$

$$(p_{d\omega}^{\uparrow}):\ \phi_\omega \pi_d^{\uparrow} - \zeta_{d\omega}^{\mathrm{p}} - \varepsilon_{i\omega}^{\mathrm{p}\uparrow} = 0, \quad \forall \omega, d \in D_e^{\mathrm{D}} \tag{A.2f}$$

$$(p_{d\omega}^{\downarrow}):\ \phi_\omega \pi_d^{\downarrow} + \zeta_{d\omega}^{\mathrm{p}} - \varepsilon_{d\omega}^{\mathrm{p}\downarrow} = 0, \quad \forall \omega, d \in D_e^{\mathrm{D}} \tag{A.2g}$$

$$(w_{r\omega}^{\uparrow}):\ \phi_\omega \pi^{\uparrow\mathrm{R}} + \zeta_{r\omega}^{\mathrm{p}} - \epsilon_{r\omega}^{\mathrm{p}\uparrow} = 0, \quad \forall \omega, r \in R_e^{\mathrm{D}} \tag{A.2h}$$

$$(w_{r\omega}^{\downarrow}):\ \phi_\omega \pi^{\downarrow\mathrm{R}} - \zeta_{r\omega}^{\mathrm{p}} - \epsilon_{r\omega}^{\mathrm{p}\downarrow} = 0, \quad \forall \omega, r \in R_e^{\mathrm{D}} \tag{A.2i}$$

$$(s_e^{\mathrm{DA}}): VOLL - \lambda_e^{\mathrm{DA}} - \Upsilon_e^{\mathrm{DA}-} + \Upsilon_e^{\mathrm{DA}+} = 0 \tag{A.2j}$$

$$(s_{n\omega}^{\mathrm{RT}}): \phi_\omega VOLL - \lambda_{n\omega}^{\mathrm{p,RT}} - \Upsilon_{n\omega}^{\mathrm{RT}-} + \Upsilon_{n\omega}^{\mathrm{RT}+} = 0,\ \forall \omega, n \in N_e^{\mathrm{D}} \tag{A.2k}$$

$$(w_{r\omega}^{\mathrm{RT}}): \phi_\omega \pi^{\mathrm{R}} - \zeta_{r\omega}^{\mathrm{p}} - \left[\lambda_{n\omega}^{\mathrm{p,RT}}\right]_{n_r} + \nu_{r\omega}^{+} - \nu_{r\omega}^{-} = 0, \quad \forall \omega, r \in R_e^{\mathrm{D}} \tag{A.2l}$$

$$(w_r^{\mathrm{DA}}): \pi^{\mathrm{R}} - \sum_\omega \phi_\omega \pi^{\mathrm{R}} - \lambda_e^{\mathrm{DA}} - \iota_r^{-} + \iota_r^{+} + \sum_\omega \zeta_{r\omega}^{\mathrm{p}} = 0, \forall r \in R_e^{\mathrm{D}} \tag{A.2m}$$

$$(p_{g\omega}^{\mathrm{RT}}): \phi_\omega \pi_g^{\mathrm{DA}} - \zeta_{g\omega}^{\mathrm{p}} - \varsigma_{g\omega}^{\mathrm{RT}-} + \varsigma_{g\omega}^{\mathrm{RT}+} - \left[\lambda_{n\omega}^{\mathrm{p,RT}}\right]_{n_g} = 0, \quad \forall \omega, g \in G_e^{\mathrm{D}} \tag{A.2n}$$

$$(q_{g\omega}^{\mathrm{RT}}): -\kappa_{g\omega}^{\mathrm{RT}-} + \kappa_{g\omega}^{\mathrm{RT}+} - \left[\lambda_{n\omega}^{\mathrm{q,RT}}\right]_{n_g} = 0, \quad \forall \omega, g \in G_e^{\mathrm{D}} \tag{A.2o}$$

$$(p_{d\omega}^{\mathrm{RT}}): -\phi_\omega \pi_d^{\mathrm{DA}} - \zeta_{d\omega}^{\mathrm{p}} - \varsigma_{d\omega}^{\mathrm{RT}-} + \varsigma_{d\omega}^{\mathrm{RT}+} + \left[\lambda_{n\omega}^{\mathrm{p,RT}} - \Upsilon_{n\omega}^{\mathrm{RT}+}\right]_{n_d} = 0, \quad \forall \omega, d \in D_e^{\mathrm{D}} \tag{A.2p}$$

$$(q_{d\omega}^{\mathrm{RT}}): -\kappa_{d\omega}^{\mathrm{RT}-} + \kappa_{d\omega}^{\mathrm{RT}+} + \left[\lambda_{n\omega}^{\mathrm{q,RT}}\right]_{n_d} = 0, \quad \forall \omega, d \in D_e^{\mathrm{D}} \tag{A.2q}$$

$$\begin{aligned}(p_{l\omega}^{\mathrm{RT}}): &\ \lambda_{n\omega}^{\mathrm{p,RT}} - \lambda_{m\omega}^{\mathrm{p,RT}} + 2\gamma_{l\omega} p_{l\omega}^{\mathrm{RT}} - \mu_{l\omega}^{\mathrm{p}} - \mu_{l'\omega}^{\mathrm{p}} + 2\eta_{l\omega} p_{l\omega}^{\mathrm{RT}} \\ &- 2\beta_{l\omega} R_l = 0, \quad \forall \omega, l = (n,m) \in L_e^{\mathrm{D}}\end{aligned} \tag{A.2r}$$

$$\begin{aligned}(q_{l\omega}^{\mathrm{RT}}): &\ \lambda_{n\omega}^{\mathrm{q,RT}} - \lambda_{m\omega}^{\mathrm{q,RT}} + 2\gamma_{l\omega} q_{l\omega}^{\mathrm{RT}} - \mu_{l\omega}^{\mathrm{q}} - \mu_{l'\omega}^{\mathrm{q}} + 2\eta_{l\omega} q_{l\omega}^{\mathrm{RT}} \\ &- 2\beta_{l\omega} X_l = 0, \quad \forall \omega, l = (n,m) \in L_e^{\mathrm{D}}\end{aligned} \tag{A.2s}$$

$$\begin{aligned}(\varphi_{l\omega}^{\mathrm{RT}}): &-\gamma_{l\omega} v_{n\omega}^{\mathrm{RT}} + \mu_{l\omega}^{\mathrm{p}} R_l + \mu_{l\omega}^{\mathrm{q}} X_l + \beta_{l\omega}(R_l^2 + X_l^2) \\ &= 0, \quad \forall \omega, l = (n,m) \in L_e^{\mathrm{D}}\end{aligned} \tag{A.2t}$$

$$(v_{n\omega}^{\mathrm{RT}}): -\gamma_{l\omega} \varphi_{l\omega}^{\mathrm{RT}} - \beta_{l'\omega} + \beta_{l\omega} - \sigma_{n\omega}^{-} + \sigma_{n\omega}^{+} = 0, \quad \forall \omega, l = (n,m) \in L_e^{\mathrm{D}} \tag{A.2u}$$

$$(p_e^{\mathrm{IO,DA}}): \pi_e^{\mathrm{IO,DA}} + \sum_\omega \left(\phi_\omega \pi_e^{\mathrm{IO,DA}} + \zeta_{e\omega}^{\mathrm{IO}}\right) - \lambda_e^{\mathrm{DA}} - \rho_e^{\mathrm{DA}-} + \rho_e^{\mathrm{DA}+} = 0 \tag{A.2v}$$

$$(p_{e\omega}^{\mathrm{IO,RT}}): \phi_\omega \pi_e^{\mathrm{IO,DA}} - \left[\lambda_{n\omega}^{\mathrm{p,RT}}\right]_{n_e^{\mathrm{LV}}} - \zeta_{e\omega}^{\mathrm{IO}} - \rho_{e\omega}^{\mathrm{RT}-} + \rho_{e\omega}^{\mathrm{RT}+} = 0, \quad \forall \omega \tag{A.2w}$$

$$(q_{e\omega}^{\mathrm{IO,RT}}): -\left[\lambda_{n\omega}^{\mathrm{q,RT}}\right]_{n_e^{\mathrm{LV}}} = 0, \quad \forall \omega \tag{A.2x}$$

$$(p_{e\omega}^{\uparrow\mathrm{IO}}): \phi_\omega \pi_e^{\uparrow\mathrm{IO}} + \zeta_{e\omega}^{\mathrm{IO}} - \epsilon_{e\omega}^{\uparrow\mathrm{IO}} = 0, \quad \forall \omega \tag{A.2y}$$

$$(p_{e\omega}^{\downarrow\mathrm{IO}}): \phi_\omega \pi_e^{\downarrow\mathrm{IO}} - \zeta_{e\omega}^{\mathrm{IO}} - \epsilon_{e\omega}^{\downarrow\mathrm{IO}} = 0, \quad \forall \omega \tag{A.2z}$$

$$0 \le \varsigma_g^{\mathrm{DA}+} \perp \overline{P}_g - \widetilde{p}_g^{\mathrm{DA}} \ge 0, \quad \forall g \in G_e^{\mathrm{D}} \tag{A.2aa}$$

$$0 \le \varsigma_g^{\mathrm{DA}-} \perp \widetilde{p}_g^{\mathrm{DA}} - \underline{P}_g \ge 0, \quad \forall g \in G_e^{\mathrm{D}} \tag{A.2ab}$$

$$0 \le \varsigma_d^{\mathrm{DA}+} \perp \overline{P}_d - \widetilde{p}_d^{\mathrm{DA}} \ge 0, \quad \forall d \in D_e^{\mathrm{D}} \tag{A.2ac}$$

$$0 \le \varsigma_d^{\mathrm{DA}-} \perp \widetilde{p}_d^{\mathrm{DA}} - \underline{P}_d \ge 0, \quad \forall d \in D_e^{\mathrm{D}} \tag{A.2ad}$$
$$0 \le \iota_r^- \perp w_r^{\mathrm{DA}} \ge 0, \quad \forall r \in R_e^{\mathrm{D}} \tag{A.2ae}$$
$$0 \le \iota_r^+ \perp W_r^{\mathrm{DA}} - w_r^{\mathrm{DA}} \ge 0, \quad \forall r \in R_e^{\mathrm{D}} \tag{A.2af}$$
$$0 \le \rho_e^{\mathrm{DA}-} \perp p_e^{\mathrm{IO,DA}} - \underline{f}_e \ge 0 \tag{A.2ag}$$
$$0 \le \rho_e^{\mathrm{DA}+} \perp \overline{f}_e - p_e^{\mathrm{IO,DA}} \ge 0 \tag{A.2ah}$$
$$0 \le \gamma_{l\omega} \perp \varphi_{l\omega}^{\mathrm{RT}} v_{n\omega}^{\mathrm{RT}} - (p_{l\omega}^{\mathrm{RT}^2} + q_{l\omega}^{\mathrm{RT}^2}) \ge 0, \ \forall \omega, l \in L_e^{\mathrm{D}} \tag{A.2ai}$$
$$0 \le \eta_{l\omega} \perp S_l - p_{l\omega}^{\mathrm{RT}^2} - q_{l\omega}^{\mathrm{RT}^2} \ge 0, \ \forall \omega, l \in L_e^{\mathrm{D}} \tag{A.2aj}$$
$$0 \le \sigma_{n\omega}^- \perp v_{n\omega}^{\mathrm{RT}} - \underline{V}_n^2 \ge 0, \quad \forall \omega, n \in N_e^{\mathrm{D}} \tag{A.2ak}$$
$$0 \le \sigma_{n\omega}^+ \perp \overline{V}_n^2 - v_{n\omega}^{\mathrm{RT}} \ge 0, \quad \forall \omega, n \in N_e^{\mathrm{D}} \tag{A.2al}$$
$$0 \le \nu_{r\omega}^- \perp w_{r\omega}^{\mathrm{RT}} \ge 0, \quad \forall \omega, r \in R_e^{\mathrm{D}} \tag{A.2am}$$
$$0 \le \nu_{r\omega}^+ \perp W_{r\omega}^{\mathrm{RT}} - w_{r\omega}^{\mathrm{RT}} \ge 0, \quad \forall \omega, r \in R_e^{\mathrm{D}} \tag{A.2an}$$
$$0 \le \varsigma_{g\omega}^{\mathrm{RT}-} \perp p_{g\omega}^{\mathrm{RT}} - \underline{P}_g \ge 0, \quad \forall \omega, g \in G_e^{\mathrm{D}} \tag{A.2ao}$$
$$0 \le \varsigma_{g\omega}^{\mathrm{RT}+} \perp \overline{P}_g - p_{g\omega}^{\mathrm{RT}} \ge 0, \quad \forall \omega, g \in G_e^{\mathrm{D}} \tag{A.2ap}$$
$$0 \le \varsigma_{d\omega}^{\mathrm{RT}-} \perp p_{d\omega}^{\mathrm{RT}} - \underline{P}_d \ge 0, \quad \forall \omega, d \in D_e^{\mathrm{D}} \tag{A.2aq}$$
$$0 \le \varsigma_{d\omega}^{\mathrm{RT}+} \perp \overline{P}_d - p_{d\omega}^{\mathrm{RT}} \ge 0, \quad \forall \omega, d \in D_e^{\mathrm{D}} \tag{A.2ar}$$
$$0 \le \kappa_{g\omega}^{\mathrm{RT}+} \perp q_{g\omega}^{\mathrm{RT}} - \underline{Q}_g \ge 0, \quad \forall \omega, g \in G_e^{\mathrm{D}} \tag{A.2as}$$
$$0 \le \kappa_{g\omega}^{\mathrm{RT}-} \perp \overline{Q}_g - q_{g\omega}^{\mathrm{RT}} \ge 0, \quad \forall \omega, g \in G_e^{\mathrm{D}} \tag{A.2at}$$
$$0 \le \kappa_{d\omega}^{\mathrm{RT}+} \perp q_{d\omega}^{\mathrm{RT}} - \underline{Q}_d \ge 0, \quad \forall \omega, d \in D_e^{\mathrm{D}} \tag{A.2au}$$
$$0 \le \kappa_{d\omega}^{\mathrm{RT}-} \perp \overline{Q}_d - q_{d\omega}^{\mathrm{RT}} \ge 0, \quad \forall \omega, d \in D_e^{\mathrm{D}} \tag{A.2av}$$
$$0 \le \rho_{e\omega}^{\mathrm{RT}-} \perp p_{e\omega}^{\mathrm{IO,RT}} - \underline{f}_e \ge 0, \quad \forall \omega \tag{A.2aw}$$
$$0 \le \rho_{e\omega}^{\mathrm{RT}+} \perp \overline{f}_e - p_{e\omega}^{\mathrm{IO,RT}} \ge 0, \quad \forall \omega \tag{A.2ax}$$
$$0 \le \epsilon_{g\omega}^{\mathrm{p}\uparrow} \perp p_{g\omega}^{\uparrow} \ge 0, \quad 0 \le \epsilon_{g\omega}^{\mathrm{p}\downarrow} \perp p_{g\omega}^{\downarrow} \ge 0, \quad \forall \omega, g \in G_e^{\mathrm{D}} \tag{A.2ay}$$
$$0 \le \epsilon_{r\omega}^{\mathrm{p}\uparrow} \perp w_{r\omega}^{\uparrow} \ge 0, \ 0 \le \epsilon_{r\omega}^{\mathrm{p}\downarrow} \perp w_{r\omega}^{\downarrow} \ge 0, \ \forall \omega, r \in R_e^{\mathrm{D}} \tag{A.2az}$$
$$0 \le \varepsilon_{d\omega}^{\mathrm{p}\uparrow} \perp p_{d\omega}^{\uparrow} \ge 0, \quad 0 \le \varepsilon_{d\omega}^{\mathrm{p}\downarrow} \perp p_{d\omega}^{\downarrow} \ge 0, \quad \forall \omega, d \in D_e^{\mathrm{D}} \tag{A.2ba}$$
$$0 \le \epsilon_{e\omega}^{\uparrow\mathrm{IO}} \perp p_{e\omega}^{\uparrow\mathrm{IO}} \ge 0, \quad 0 \le \epsilon_{e\omega}^{\downarrow\mathrm{IO}} \perp p_{e\omega}^{\downarrow\mathrm{IO}} \ge 0, \quad \forall \omega \tag{A.2bb}$$
$$0 \le \Upsilon_{n\omega}^{\mathrm{RT}-} \perp s_{n\omega}^{\mathrm{RT}} \ge 0, \forall n, \omega \tag{A.2bc}$$
$$0 \le \Upsilon_{n\omega}^{\mathrm{RT}+} \perp \sum_{d \in D_n} p_{d\omega}^{\mathrm{RT}} - s_{n\omega}^{\mathrm{RT}} \ge 0, \ \forall n, \omega \tag{A.2bd}$$
$$0 \le \Upsilon_e^{\mathrm{DA}-} \perp s_e^{\mathrm{DA}} \ge 0 \tag{A.2be}$$
$$0 \le \Upsilon_e^{\mathrm{DA}+} \perp \sum_d p_d^{\mathrm{DA}} - s_e^{\mathrm{DA}} \ge 0. \tag{A.2bf}$$

Appendix B. KKT Conditions of the Lower-Level Problem (3) Representing the Day-Ahead Market Clearing

For convenience, the lower-level problem (3) within the paper is repeated here by (B.1) below, while the dual variable for every constraint is defined:

$$\max_{\Xi^{\mathrm{DA}}} \mathcal{SW}^{\mathrm{DA}} = \sum_{d\in D} \pi_d^{\mathrm{DA}} \widehat{p}_d^{\mathrm{DA}} - \sum_{g\in G} \pi_g^{\mathrm{DA}} \widehat{p}_g^{\mathrm{DA}} - VOLL\ s^{\mathrm{DA}} - \pi^{\mathrm{R}} \sum_r w_r^{\mathrm{DA}} \tag{B.1a}$$

subject to:

$$\sum_{g\in G} \widehat{p}_g^{\mathrm{DA}} - \sum_{d\in D} \widehat{p}_d^{\mathrm{DA}} + \sum_r w_r^{\mathrm{DA}} + s^{\mathrm{DA}} = 0,\ :(\lambda^{\mathrm{T,DA}}) \tag{B.1b}$$

$$\underline{P}_g \le \widehat{p}_g^{\mathrm{DA}} \le \widetilde{p}_g^{\mathrm{DA}},\ \forall g \in G_e^{\mathrm{D}},\ \forall e\in E\ :(\varsigma_{ge}^{\mathrm{T,DA}-}, \varsigma_{ge}^{\mathrm{T,DA}+}) \tag{B.1c}$$

$$\underline{P}_g \le \widehat{p}_g^{\mathrm{DA}} \le \overline{P}_g,\ \forall g \in G^{\mathrm{T}}\ :(\sigma_g^{\mathrm{T,DA}-}, \sigma_g^{\mathrm{T,DA}+}) \tag{B.1d}$$

$$\underline{P}_d \le \widehat{p}_d^{\mathrm{DA}} \le \widetilde{p}_d^{\mathrm{DA}},\ \forall d \in D_e^{\mathrm{D}},\ \forall e\in E\ :(\varsigma_{de}^{\mathrm{T,DA}-}, \varsigma_{de}^{\mathrm{T,DA}+}) \tag{B.1e}$$

$$\underline{P}_d \le \widehat{p}_d^{\mathrm{DA}} \le \overline{P}_d,\ \forall d \in D^{\mathrm{T}}\ :(\sigma_d^{\mathrm{T,DA}-}, \sigma_d^{\mathrm{T,DA}+}) \tag{B.1f}$$

$$0 \le w_r^{\mathrm{DA}} \le W_r^{\mathrm{DA}},\ \forall r\in R\ :(\nu_r^{\mathrm{T,DA}-}, \nu_r^{\mathrm{T,DA}+}) \tag{B.1g}$$

$$0 \le s^{\mathrm{DA}} \le \sum_d \widehat{p}_d^{\mathrm{DA}},\ :(\rho^{\mathrm{T,DA}-}, \rho^{\mathrm{T,DA}+}). \tag{B.1h}$$

Recall that $\widetilde{p}_g^{\mathrm{DA}}$ and $\widetilde{p}_d^{\mathrm{DA}}$ are the outputs of problem (A.1), and treated as parameters within (B.1). Therefore, the KKT conditions associated with (B.1) are

$$\text{(B.1b)} \tag{B.2a}$$

$$(\widehat{p}_g^{\mathrm{DA}}):\quad \pi_g^{\mathrm{DA}} - \left[\varsigma_{ge}^{\mathrm{T,DA}-} - \varsigma_{ge}^{\mathrm{T,DA}+}\right]_{g\in G_e^{\mathrm{D}}} - \left[\sigma_g^{\mathrm{T,DA}-} - \sigma_g^{\mathrm{T,DA}+}\right]_{g\in G^{\mathrm{T}}} - \lambda^{\mathrm{T,DA}} = 0,\quad \forall g\in G \tag{B.2b}$$

$$(\widehat{p}_d^{\mathrm{DA}}):\quad -\pi_d^{\mathrm{DA}} - \left[\varsigma_{de}^{\mathrm{T,DA}-} - \varsigma_{de}^{\mathrm{T,DA}+}\right]_{d\in D_e^{\mathrm{D}}} - \left[\sigma_d^{\mathrm{T,DA}-} - \sigma_d^{\mathrm{T,DA}+}\right]_{d\in D^{\mathrm{T}}} - \rho^{\mathrm{T,DA}+} + \lambda^{\mathrm{T,DA}} = 0,\quad \forall d\in D \tag{B.2c}$$

$$(s^{\mathrm{DA}}):\quad VOLL - \lambda^{\mathrm{T,DA}} - \rho^{\mathrm{T,DA}-} + \rho^{\mathrm{T,DA}+} = 0 \tag{B.2d}$$

$$(w_r^{\mathrm{DA}}):\quad \pi^{\mathrm{R}} - \lambda^{\mathrm{T,DA}} - \left[\nu_r^{\mathrm{T,DA}-} - \nu_r^{\mathrm{T,DA}+}\right] = 0,\ \forall r\in R \tag{B.2e}$$

$$0 \le \varsigma_{ge}^{\mathrm{T,DA}-} \perp \widehat{p}_g^{\mathrm{DA}} - \underline{P}_g \ge 0 \quad \forall g, e \tag{B.2f}$$

$$0 \le \varsigma_{ge}^{\mathrm{T,DA}+} \perp \widetilde{p}_g^{\mathrm{DA}} - \widehat{p}_g^{\mathrm{DA}} \ge 0 \quad \forall g\in G_e^{\mathrm{D}}, e\in E \tag{B.2g}$$

$$0 \le \sigma_g^{\mathrm{T,DA}+} \perp \overline{P}_g - \widehat{p}_g^{\mathrm{DA}} \ge 0 \quad \forall g\in G^{\mathrm{T}} \tag{B.2h}$$

$$0 \le \varsigma_{de}^{\mathrm{T,DA}-} \perp \widehat{p}_d^{\mathrm{DA}} - \underline{P}_d \ge 0 \quad \forall d, e \tag{B.2i}$$

$$0 \le \varsigma_{de}^{\mathrm{T,DA}+} \perp \widetilde{p}_d^{\mathrm{DA}} - \widehat{p}_d^{\mathrm{DA}} \ge 0 \quad \forall d\in D_e^{\mathrm{D}}, e\in E \tag{B.2j}$$

$$0 \le \sigma_d^{\mathrm{T,DA}+} \perp \overline{P}_d - \widehat{p}_d^{\mathrm{DA}} \ge 0 \quad \forall d\in D^{\mathrm{T}} \tag{B.2k}$$

$$0 \le \nu_r^{\mathrm{T,DA}-} \perp w_r^{\mathrm{DA}} \ge 0,\ \forall r\in R \tag{B.2l}$$

$$0 \le \nu_r^{\mathrm{T,DA}+} \perp W_r^{\mathrm{DA}} - w_r^{\mathrm{DA}} \ge 0,\ \forall r\in R \tag{B.2m}$$

$$0 \le \rho^{\mathrm{T,DA}-} \perp s^{\mathrm{DA}} \ge 0 \tag{B.2n}$$

$$0 \leq \rho^{\mathrm{T,DA}+} \perp \sum_{d} \widehat{p}_d^{\mathrm{DA}} - s^{\mathrm{DA}} \geq 0. \tag{B.2o}$$

Appendix C. KKT Conditions of the Lower-Level Problem (4) Representing the Real-Time Market Clearing

Recall that the KKT conditions of the lower-level problem (4) for the real-time market clearing under each scenario ω are not used in the paper, because the proposed Benders' decomposition renders this lower-level problem to be solved as a single problem. However, the KKT conditions derived in this appendix for SOCP problem (4) are used for proving the redundancy of the DSO market-clearing problem (A.1).

Pursuing convenience, the lower-level problem (4) for each scenario ω is repeated here by (C.1) below, while the objective function is multiplied by the probability of the corresponding scenario, i.e., ϕ_ω, and the dual variable for every constraint is defined:

$$\min_{\Xi^{\mathrm{RT}}} \phi_\omega \ \Delta\mathrm{Cost}_\omega^{\mathrm{RT}} =$$

$$\phi_\omega \Bigg[\sum_{g \in G} \Big(\pi_g^{\mathrm{DA}} (p_{g\omega}^{\mathrm{RT}} - \widehat{p}_g^{\mathrm{DA}}) + \pi_g^{\uparrow} p_{g\omega}^{\uparrow} + \pi_g^{\downarrow} p_{g\omega}^{\downarrow} \Big) + \sum_{d \in D} \Big(\pi_d^{\mathrm{DA}} (\widehat{p}_d^{\mathrm{DA}} - p_{d\omega}^{\mathrm{RT}}) + \pi_d^{\uparrow} p_{d\omega}^{\uparrow} + \pi_d^{\downarrow} p_{d\omega}^{\downarrow} \Big)$$

$$+ \sum_{n \in N} VOLL \ s_{n\omega}^{\mathrm{RT}} + \sum_{r} \Big(\pi^{\mathrm{R}} (w_{r\omega}^{\mathrm{RT}} - w_r^{\mathrm{DA}}) + \pi^{\uparrow\mathrm{R}} w_{r\omega}^{\uparrow} + \pi^{\downarrow\mathrm{R}} w_{r\omega}^{\downarrow} \Big) \Bigg] \tag{C.1a}$$

subject to:

$$p_{l\omega}^{\mathrm{RT}} = B_l (\theta_{n\omega} - \theta_{m\omega}), \quad \forall l \in L^{\mathrm{T}}, \ : (\gamma_{l\omega}^{\mathrm{T}}) \tag{C.1b}$$

$$p_{l\omega}^{\mathrm{RT}} \leq S_l, \ \forall l \in L^{\mathrm{T}}, \ : (\eta_{l\omega}^{\mathrm{T}}) \tag{C.1c}$$

$$p_{g\omega}^{\mathrm{RT}} = \widehat{p}_g^{\mathrm{DA}} + p_{g\omega}^{\uparrow} - p_{g\omega}^{\downarrow}, \quad \forall g \in G, \ : (\zeta_{g\omega}^{\mathrm{p,RT}}) \tag{C.1d}$$

$$p_{d\omega}^{\mathrm{RT}} = \widehat{p}_d^{\mathrm{DA}} - p_{d\omega}^{\uparrow} + p_{d\omega}^{\downarrow}, \quad \forall d \in D, \ : (\zeta_{d\omega}^{\mathrm{p,RT}}) \tag{C.1e}$$

$$w_{r\omega}^{\mathrm{RT}} = w_r^{\mathrm{DA}} + w_{r\omega}^{\uparrow} - w_{r\omega}^{\downarrow}, \ \forall r \in R, \ : (\zeta_{r\omega}^{\mathrm{p,RT}}) \tag{C.1f}$$

$$\sum_{g \in G_n} p_{g\omega}^{\mathrm{RT}} - \sum_{d \in D_n} p_{d\omega}^{\mathrm{RT}} + \sum_{r \in R_n} w_{r\omega}^{\mathrm{RT}} + s_{n\omega}^{\mathrm{RT}} = \sum_{l \in n \rightarrow} p_{l\omega}^{\mathrm{RT}} - \sum_{l \in \rightarrow n} p_{l\omega}^{\mathrm{RT}}, \ \forall n \in N, \ : (\lambda_{n\omega}^{\mathrm{p,RT}}) \tag{C.1g}$$

$$\sum_{g \in G_n} q_{g\omega}^{\mathrm{RT}} - \sum_{d \in D_n} q_{d\omega}^{\mathrm{RT}} + s_{n\omega}^{\mathrm{q,RT}} = \sum_{l \in n \rightarrow} q_{l\omega}^{\mathrm{RT}} - \sum_{l \in \rightarrow n} q_{l\omega}^{\mathrm{RT}}, \ \forall n \in N_e^{\mathrm{D}}, \ : (\lambda_{n\omega}^{\mathrm{q,RT}}) \tag{C.1h}$$

$$p_{l\omega}^{\mathrm{RT}^2} + q_{l\omega}^{\mathrm{RT}^2} \leq \varphi_{l\omega}^{\mathrm{RT}} v_{n\omega}^{\mathrm{RT}}, \ \forall l \in L_e^{\mathrm{D}} \cup l_e, \ : (\gamma_{l\omega}^{\mathrm{D,RT}}) \tag{C.1i}$$

$$p_{l\omega}^{\mathrm{RT}} + p_{l'\omega}^{\mathrm{RT}} = R_l \varphi_{l\omega}^{\mathrm{RT}}, \ \forall l \in L_e^{\mathrm{D}} \cup l_e, \ : (\mu_{l\omega}^{\mathrm{p,RT}}) \tag{C.1j}$$

$$q_{l\omega}^{\mathrm{RT}} + q_{l'\omega}^{\mathrm{RT}} = X_l \varphi_{l\omega}^{\mathrm{RT}}, \ \forall l \in L_e^{\mathrm{D}} \cup l_e, \ : (\mu_{l\omega}^{\mathrm{q,RT}}) \tag{C.1k}$$

$$p_{l\omega}^{\mathrm{RT}^2} + q_{l\omega}^{\mathrm{RT}^2} \leq S_l^2, \ \forall l \in L_e^{\mathrm{D}} \cup l_e, \ : (\eta_{l\omega}^{\mathrm{D}}) \tag{C.1l}$$

$$v_{m\omega}^{\mathrm{RT}} = v_{n\omega}^{\mathrm{RT}} - 2(R_l p_{l\omega}^{\mathrm{RT}} + X_l q_{l\omega}^{\mathrm{RT}}) + (R_l^2 + X_l^2) \varphi_{l\omega}^{\mathrm{RT}}, \ \forall l \in L_e^{\mathrm{D}} \cup l_e, \ : (\beta_{l\omega}^{\mathrm{RT}}) \tag{C.1m}$$

$$\underline{V}_n^2 \leq v_{n\omega}^{\mathrm{RT}} \leq \overline{V}_n^2, \quad \forall e, n \in N_e^{\mathrm{D}}, \ : (\sigma_{n\omega}^{\mathrm{RT}-}, \sigma_{n\omega}^{\mathrm{RT}+}) \tag{C.1n}$$

$$0 \leq w_{r\omega}^{\mathrm{RT}} \leq W_{r\omega}^{\mathrm{RT}}, \quad \forall r \in R, \ : (\nu_{r\omega}^{\mathrm{RT}-}, \nu_{r\omega}^{\mathrm{RT}+}) \tag{C.1o}$$

$$\underline{P}_g \le p^{\mathrm{RT}}_{g\omega} \le \overline{P}_g, \quad \forall g \in G, \ : (\varsigma^{\mathrm{RT}-}_{g\omega}, \varsigma^{\mathrm{RT}+}_{g\omega}) \tag{C.1p}$$

$$\underline{P}_d \le p^{\mathrm{RT}}_{d\omega} \le \overline{P}_d, \quad \forall d \in D, \ : (\varsigma^{\mathrm{RT}-}_{d\omega}, \varsigma^{\mathrm{RT}+}_{d\omega}) \tag{C.1q}$$

$$\underline{Q}_g \le q^{\mathrm{RT}}_{g\omega} \le \overline{Q}_g, \quad \forall g \in G^{\mathrm{D}}_e, \ : (\kappa^{\mathrm{RT}-}_{g\omega}, \kappa^{\mathrm{RT}+}_{g\omega}) \tag{C.1r}$$

$$\underline{Q}_d \le q^{\mathrm{RT}}_{d\omega} \le \overline{Q}_d, \quad \forall d \in D^{\mathrm{D}}_e, \ : (\kappa^{\mathrm{RT}-}_{d\omega}, \kappa^{\mathrm{RT}+}_{d\omega}) \tag{C.1s}$$

$$0 \le s^{\mathrm{RT}}_{n\omega} \le \sum_{d \in D_n} p^{\mathrm{RT}}_{d\omega}, \ \forall n \in N, \ : (\Upsilon^{\mathrm{RT}-}_{n\omega}, \Upsilon^{\mathrm{RT}+}_{n\omega}) \tag{C.1t}$$

$$p^{\uparrow}_{g\omega} \ge 0, \quad p^{\downarrow}_{g\omega} \ge 0, \ \forall g, \ : (\epsilon^{\uparrow,\mathrm{RT}}_{g\omega}, \epsilon^{\downarrow,\mathrm{RT}}_{g\omega}) \tag{C.1u}$$

$$p^{\uparrow}_{d\omega} \ge 0, \quad p^{\downarrow}_{d\omega} \ge 0, \ \forall d, \ : (\epsilon^{\uparrow,\mathrm{RT}}_{d\omega}, \epsilon^{\downarrow,\mathrm{RT}}_{d\omega}) \tag{C.1v}$$

$$w^{\uparrow}_{r\omega} \ge 0, \quad w^{\downarrow}_{r\omega} \ge 0, \forall r, \ : (\varepsilon^{\uparrow,\mathrm{RT}}_{r\omega}, \varepsilon^{\downarrow,\mathrm{RT}}_{r\omega}). \tag{C.1w}$$

The KKT conditions associated with (C.1) are

$$(\mathrm{C.1b}), (\mathrm{C.1d}) - (\mathrm{C.1h}), (\mathrm{C.1j}), (\mathrm{C.1k}), (\mathrm{C.1m}) \tag{C.2a}$$

$$(p^{\uparrow}_{g\omega}): \ \phi_\omega \pi^{\uparrow}_g + \zeta^{\mathrm{p}}_{g\omega} - \epsilon^{\mathrm{p}\uparrow}_{g\omega} = 0, \quad \forall g \in G^{\mathrm{D}}_e \tag{C.2b}$$

$$(p^{\downarrow}_{g\omega}): \ \phi_\omega \pi^{\downarrow}_g - \zeta^{\mathrm{p}}_{g\omega} - \epsilon^{\mathrm{p}\downarrow}_{g\omega} = 0, \quad \forall g \in G^{\mathrm{D}}_e \tag{C.2c}$$

$$(p^{\uparrow}_{d\omega}): \ \phi_\omega \pi^{\uparrow}_d - \zeta^{\mathrm{p}}_{d\omega} - \varepsilon^{\mathrm{p}\uparrow}_{i\omega} = 0, \quad \forall d \in D^{\mathrm{D}}_e \tag{C.2d}$$

$$(p^{\downarrow}_{d\omega}): \ \phi_\omega \pi^{\downarrow}_d + \zeta^{\mathrm{p}}_{d\omega} - \varepsilon^{\mathrm{p}\downarrow}_{d\omega} = 0, \quad \forall d \in D^{\mathrm{D}}_e \tag{C.2e}$$

$$(w^{\uparrow}_{r\omega}): \ \phi_\omega \pi^{\uparrow\mathrm{R}} + \zeta^{\mathrm{p}}_{r\omega} - \epsilon^{\mathrm{p}\uparrow}_{r\omega} = 0, \quad \forall r \in R^{\mathrm{D}}_e \tag{C.2f}$$

$$(w^{\downarrow}_{r\omega}): \ \phi_\omega \pi^{\downarrow\mathrm{R}} - \zeta^{\mathrm{p}}_{r\omega} - \epsilon^{\mathrm{p}\downarrow}_{r\omega} = 0, \quad \forall r \in R^{\mathrm{D}}_e \tag{C.2g}$$

$$(s^{\mathrm{RT}}_{n\omega}): \phi_\omega VOLL - \lambda^{\mathrm{p,RT}}_{n\omega} - \Upsilon^{\mathrm{RT}-}_{n\omega} + \Upsilon^{\mathrm{RT}+}_{n\omega} = 0, \ \forall n \in N \tag{C.2h}$$

$$(w^{\mathrm{RT}}_{r\omega}): \phi_\omega \pi^{\mathrm{R}} - \zeta^{\mathrm{p}}_{r\omega} - \left[\lambda^{\mathrm{p,RT}}_{n\omega}\right]_{n_r} + \nu^{+}_{r\omega} - \nu^{-}_{r\omega} = 0, \quad \forall r \in R^{\mathrm{D}}_e \tag{C.2i}$$

$$(p^{\mathrm{RT}}_{g\omega}): \phi_\omega \pi^{\mathrm{DA}}_g - \zeta^{\mathrm{p}}_{g\omega} - \varsigma^{\mathrm{RT}-}_{g\omega} + \varsigma^{\mathrm{RT}+}_{g\omega} - \left[\lambda^{\mathrm{p,RT}}_{n\omega}\right]_{n_g} = 0, \quad \forall g \in G \tag{C.2j}$$

$$(q^{\mathrm{RT}}_{g\omega}): -\kappa^{\mathrm{RT}-}_{g\omega} + \kappa^{\mathrm{RT}+}_{g\omega} - \left[\lambda^{\mathrm{q,RT}}_{n\omega}\right]_{n_g} = 0, \quad \forall g \in G^{\mathrm{D}}_e \tag{C.2k}$$

$$(p^{\mathrm{RT}}_{d\omega}): -\phi_\omega \pi^{\mathrm{DA}}_d - \zeta^{\mathrm{p}}_{d\omega} - \varsigma^{\mathrm{RT}-}_{d\omega} + \varsigma^{\mathrm{RT}+}_{d\omega} + \left[\lambda^{\mathrm{p,RT}}_{n\omega} - \Upsilon^{\mathrm{RT}+}_{n\omega}\right]_{n_d} = 0, \quad \forall d \in D \tag{C.2l}$$

$$(q^{\mathrm{RT}}_{d\omega}): -\kappa^{\mathrm{RT}-}_{d\omega} + \kappa^{\mathrm{RT}+}_{d\omega} + \left[\lambda^{\mathrm{q,RT}}_{n\omega}\right]_{n_d} = 0, \quad \forall d \in D^{\mathrm{D}}_e \tag{C.2m}$$

$$\begin{aligned}(p^{\mathrm{RT}}_{l\omega}): \lambda^{\mathrm{p,RT}}_{n\omega} - \lambda^{\mathrm{p,RT}}_{m\omega} + \left[2\gamma_{l\omega} p^{\mathrm{RT}}_{l\omega} - \mu^{\mathrm{p}}_{l\omega} - \mu^{\mathrm{p}}_{l'\omega} + 2\eta_{l\omega} p^{\mathrm{RT}}_{l\omega} - 2\beta_{l\omega} R_l\right]_{l \in L^{\mathrm{D}}_e} \\ + \left[\gamma^{\mathrm{T}}_{l\omega} + \eta^{\mathrm{T}}_{l\omega}\right]_{l \in L^{\mathrm{T}}} = 0, \quad \forall l \in L\end{aligned} \tag{C.2n}$$

$$(q^{\mathrm{RT}}_{l\omega}): \lambda^{\mathrm{q,RT}}_{n\omega} - \lambda^{\mathrm{q,RT}}_{m\omega} + \left[2\gamma_{l\omega} q^{\mathrm{RT}}_{l\omega} - \mu^{\mathrm{q}}_{l\omega} - \mu^{\mathrm{q}}_{l'\omega} + 2\eta_{l\omega} q^{\mathrm{RT}}_{l\omega} - 2\beta_{l\omega} X_l\right]_{l \in L^{\mathrm{D}}_e} = 0, \quad \forall l \in L \tag{C.2o}$$

$$(\varphi^{\mathrm{RT}}_{l\omega}): -\gamma_{l\omega} v^{\mathrm{RT}}_{n\omega} + \mu^{\mathrm{p}}_{l\omega} R_l + \mu^{\mathrm{q}}_{l\omega} X_l + \beta_{l\omega}(R_l^2 + X_l^2) = 0, \quad \forall \omega, l = (n,m) \in L^{\mathrm{D}}_e \tag{C.2p}$$

$$(v^{\mathrm{RT}}_{n\omega}): -\gamma_{l\omega} \varphi^{\mathrm{RT}}_{l\omega} - \beta_{l'\omega} + \beta_{l\omega} - \sigma^{-}_{n\omega} + \sigma^{+}_{n\omega} = 0, \quad \forall \omega, l = (n,m) \in L^{\mathrm{D}}_e \tag{C.2q}$$

$$0 \le \gamma_{l\omega} \perp \varphi^{\mathrm{RT}}_{l\omega} v^{\mathrm{RT}}_{n\omega} - (p^{\mathrm{RT}^2}_{l\omega} + q^{\mathrm{RT}^2}_{l\omega}) \ge 0, \ \forall \omega, l \in L^{\mathrm{D}}_e \tag{C.2r}$$

$$0 \le \eta_{l\omega} \perp S_l - p^{\mathrm{RT}^2}_{l\omega} - q^{\mathrm{RT}^2}_{l\omega} \ge 0, \ \forall \omega, l \in L^{\mathrm{D}}_e \tag{C.2s}$$

$$0 \le \sigma^{-}_{n\omega} \perp v^{\mathrm{RT}}_{n\omega} - \underline{V}^2_n \ge 0, \quad \forall \omega, n \in N^{\mathrm{D}}_e \tag{C.2t}$$

$$0 \leq \sigma^{+}_{n\omega} \perp \overline{V}^{2}_{n} - v^{\mathrm{RT}}_{n\omega} \geq 0, \quad \forall \omega, n \in N^{\mathrm{D}}_{e} \tag{C.2u}$$
$$0 \leq \nu^{-}_{r\omega} \perp w^{\mathrm{RT}}_{r\omega} \geq 0, \quad \forall \omega, r \in R^{\mathrm{D}}_{e} \tag{C.2v}$$
$$0 \leq \nu^{+}_{r\omega} \perp W^{\mathrm{RT}}_{r\omega} - w^{\mathrm{RT}}_{r\omega} \geq 0, \quad \forall \omega, r \in R^{\mathrm{D}}_{e} \tag{C.2w}$$
$$0 \leq \varsigma^{\mathrm{RT}-}_{g\omega} \perp p^{\mathrm{RT}}_{g\omega} - \underline{P}_{g} \geq 0, \quad \forall \omega, g \in G^{\mathrm{D}}_{e} \tag{C.2x}$$
$$0 \leq \varsigma^{\mathrm{RT}+}_{g\omega} \perp \overline{P}_{g} - p^{\mathrm{RT}}_{g\omega} \geq 0, \quad \forall \omega, g \in G^{\mathrm{D}}_{e} \tag{C.2y}$$
$$0 \leq \varsigma^{\mathrm{RT}-}_{d\omega} \perp p^{\mathrm{RT}}_{d\omega} - \underline{P}_{d} \geq 0, \quad \forall \omega, d \in D^{\mathrm{D}}_{e} \tag{C.2z}$$
$$0 \leq \varsigma^{\mathrm{RT}+}_{d\omega} \perp \overline{P}_{d} - p^{\mathrm{RT}}_{d\omega} \geq 0, \quad \forall \omega, d \in D^{\mathrm{D}}_{e} \tag{C.2aa}$$
$$0 \leq \kappa^{\mathrm{RT}+}_{g\omega} \perp q^{\mathrm{RT}}_{g\omega} - \underline{Q}_{g} \geq 0, \quad \forall \omega, g \in G^{\mathrm{D}}_{e} \tag{C.2ab}$$
$$0 \leq \kappa^{\mathrm{RT}-}_{g\omega} \perp \overline{Q}_{g} - q^{\mathrm{RT}}_{g\omega} \geq 0, \quad \forall \omega, g \in G^{\mathrm{D}}_{e} \tag{C.2ac}$$
$$0 \leq \kappa^{\mathrm{RT}+}_{d\omega} \perp q^{\mathrm{RT}}_{d\omega} - \underline{Q}_{d} \geq 0, \quad \forall \omega, d \in D^{\mathrm{D}}_{e} \tag{C.2ad}$$
$$0 \leq \kappa^{\mathrm{RT}-}_{d\omega} \perp \overline{Q}_{d} - q^{\mathrm{RT}}_{d\omega} \geq 0, \quad \forall \omega, d \in D^{\mathrm{D}}_{e} \tag{C.2ae}$$
$$0 \leq \rho^{\mathrm{RT}-}_{e\omega} \perp p^{\mathrm{IO,RT}}_{e\omega} - \underline{f}_{e} \geq 0, \quad \forall \omega \tag{C.2af}$$
$$0 \leq \rho^{\mathrm{RT}+}_{e\omega} \perp \overline{f}_{e} - p^{\mathrm{IO,RT}}_{e\omega} \geq 0, \quad \forall \omega \tag{C.2ag}$$
$$0 \leq \epsilon^{\mathrm{p}\uparrow}_{g\omega} \perp p^{\uparrow}_{g\omega} \geq 0, \quad 0 \leq \epsilon^{\mathrm{p}\downarrow}_{g\omega} \perp p^{\downarrow}_{g\omega} \geq 0, \quad \forall \omega, g \in G^{\mathrm{D}}_{e} \tag{C.2ah}$$
$$0 \leq \epsilon^{\mathrm{p}\uparrow}_{r\omega} \perp w^{\uparrow}_{r\omega} \geq 0,\ 0 \leq \epsilon^{\mathrm{p}\downarrow}_{r\omega} \perp w^{\downarrow}_{r\omega} \geq 0,\ \forall \omega, r \in R^{\mathrm{D}}_{e} \tag{C.2ai}$$
$$0 \leq \varepsilon^{\mathrm{p}\uparrow}_{d\omega} \perp p^{\uparrow}_{d\omega} \geq 0, \quad 0 \leq \varepsilon^{\mathrm{p}\downarrow}_{d\omega} \perp p^{\downarrow}_{d\omega} \geq 0, \quad \forall \omega, d \in D^{\mathrm{D}}_{e} \tag{C.2aj}$$
$$0 \leq \epsilon^{\uparrow\mathrm{IO}}_{e\omega} \perp p^{\uparrow\mathrm{IO}}_{e\omega} \geq 0, \quad 0 \leq \epsilon^{\downarrow\mathrm{IO}}_{e\omega} \perp p^{\downarrow\mathrm{IO}}_{e\omega} \geq 0, \quad \forall \omega \tag{C.2ak}$$
$$0 \leq \Upsilon^{\mathrm{RT}-}_{n\omega} \perp s^{\mathrm{RT}}_{n\omega} \geq 0, \forall n, \omega \tag{C.2al}$$
$$0 \leq \Upsilon^{\mathrm{RT}+}_{n\omega} \perp \sum_{d \in D_n} p^{\mathrm{RT}}_{d\omega} - s^{\mathrm{RT}}_{n\omega} \geq 0,\ \forall n, \omega \tag{C.2am}$$
$$0 \leq \Upsilon^{\mathrm{DA}-}_{e} \perp s^{\mathrm{DA}}_{e} \geq 0 \tag{C.2an}$$
$$0 \leq \Upsilon^{\mathrm{DA}+}_{e} \perp \sum_{d} p^{\mathrm{DA}}_{d} - s^{\mathrm{DA}}_{e} \geq 0. \tag{C.2ao}$$

Appendix D. Proof

Every condition within (A.2) related to the DSO market is included within either (B.2) associated with the day-ahead market clearing or (C.2) corresponding to the real-time market clearing under each scenario ω, or can be built by a combination of conditions within (B.2) and (C.2). This concludes that the DSO market-clearing problem is redundant, and therefore, it can be removed.

Appendix E. Generated scenarios for the 24-bus case study

The co-variance matrix is calculated from equation A.2 in the main paper, by inserting the distances in table B.6 into it. We chose $\kappa = 0.1$ as the distance correlation parameter. The co-variance matrix is thus:

$$\Sigma_{rw} = \begin{bmatrix} 2.0441 & 1.5467 & 0.1784 & -0.0437 & -0.0469 & -0.0346 - 0.0723 \\ 1.5467 & 2.0441 & 0.2639 & -0.0409 & -0.0437 & -0.0341 - 0.0714 \\ 0.1784 & 0.2639 & 0.7359 & -0.0233 & -0.0225 & -0.0196 - 0.0410 \\ -0.0437 & -0.0409 & -0.0233 & 0.3271 & 0.2475 & 0.04250.0547 \\ -0.0469 & -0.0437 & -0.0225 & 0.2475 & 0.3271 & 0.04780.0653 \\ -0.0346 & -0.0341 & -0.0196 & 0.0425 & 0.0478 & 0.08180.1142 \\ -0.0723 & -0.0714 & -0.0410 & 0.0547 & 0.0653 & 0.11420.3271 \end{bmatrix} \times 10^4 \tag{E.1}$$

In order to give the reader a correlation in the same units as the mean of the drawn sample we also present the pearsons correlation matrix which is in normalized units:

$$\rho_{rw} = \begin{bmatrix} 1.0000 & 0.7567 & 0.1454 & -0.0534 & -0.0573 & -0.0847 & -0.0884 \\ 0.7567 & 1.0000 & 0.2152 & -0.0501 & -0.0534 & -0.0834 & -0.0873 \\ 0.1454 & 0.2152 & 1.0000 & -0.0475 & -0.0458 & -0.0799 & -0.0836 \\ -0.0534 & -0.0501 & -0.0475 & 1.0000 & 0.7567 & 0.2596 & 0.1672 \\ -0.0573 & -0.0534 & -0.0458 & 0.7567 & 1.0000 & 0.2924 & 0.1998 \\ -0.0847 & -0.0834 & -0.0799 & 0.2596 & 0.2924 & 1.0000 & 0.6986 \\ -0.0884 & -0.0873 & -0.0836 & 0.1672 & 0.1998 & 0.6986 & 1.0000 \end{bmatrix} \tag{E.2}$$

We draw random samples from the Gaussian mixture model as detailed in Appendix A, which are given in table E.7 for the 20 in-sample scenarios used in the case study.

Scenario	W_1	W_2	W_3	W_4	W_5	W_6	W_7
ω_1	333.6814	58.7427	106.8234	41.1964	0	0	12.3438
ω_2	467.4396	244.9183	312.9845	56.0247	43.3885	27.5563	30.2669
ω_3	284.4720	364.3555	199.5899	58.0723	3.3824	26.2587	105.4526
ω_4	219.4189	251.3683	40.4141	42.2516	8.4280	34.7555	7.8211
ω_5	0	0	112.6440	48.9591	16.6905	52.5694	12.6823
ω_6	36.9660	75.2027	70.4812	0	0	3.1812	39.3380
ω_7	230.0818	110.7641	51.2999	0	0	0	68.5206
ω_8	124.5832	90.5776	137.9857	0	0	18.8107	78.9598
ω_9	83.7720	0	0	0	73.2307	2.0071	45.8873
ω_{10}	198.5331	96.1273	0	0	0	2.2841	6.1913
ω_{11}	113.1748	121.5212	182.2171	0	15.5689	30.2558	39.3447
ω_{12}	0	0	21.2978	74.1063	160.9742	15.6578	41.2601
ω_{13}	0	0	0	86.7459	42.0339	27.7790	29.7465
ω_{14}	0	52.3388	104.0753	126.0792	95.1533	0	0
ω_{15}	0	45.3190	53.1552	112.7673	19.6549	12.7770	0
ω_{16}	189.4699	289.6591	0	0.4854	0	38.4201	50.3321
ω_{17}	0	0	0	0	0	19.4365	43.5836
ω_{18}	232.6866	226.1959	36.7433	26.8137	16.3969	0	0
ω_{19}	0	0	0	0	0	22.2595	44.2755
ω_{20}	0	80.3570	35.8253	0	50.2969	9.9160	0.6579

Table E.7: The 20 scenarios for the in-sample optimization of the large 24-bus case study. These scenarios are used for the case with wind-penetration of 100% and are scaled linearly with a factor to the desired wind-penetration.

Appendix F. Input data for case 24-bus case study

Generator	Location in network	π_g^{DA}	$\pi_g^{\uparrow}$	$\pi_g^{\downarrow}$	$\overline{P}$
G_1	node 1	19.02	20.800	22.9	400
G_2	node 2	19.32	17.800	19.9	252
G_3	node 7	19.7	17.000	8.00	350
G_4	node 13	16.93	13.700	8.30	591
G_5	DSO 1	23.9	2.500	0.60	400
G_6	node 15	18.52	17.800	19.2	700
G_7	node 16	18.62	10.800	8.20	500
G_8	DSO 5	21.1	1	1.20	400
G_9	node 21	19.27	12.4	4.70	650
G_{10}	node 22	19.22	14	5	700
G_{11}	node 23	18.1	14.800	16.2	500
G_{12}	node 23	18.99	11.100	13.9	200
G_{13}	DSO 2	20.89	3	1.70	400
G_{14}	DSO 3	20.9	3	1	400
G_{15}	DSO 4	20.3	3.00	1.00	400
G_{16}	DSO 5	20.1	3.1	1.10	400
G_{17}	node 1	19.9	11.800	15.5	150
G_{18}	node 21	19	10.1	15.9	150
G_{19}	node 15	22.52	10.800	15.2	155

Table F.8: Generator offer prices for the large 24-bus case study.

From bus	To bus	Resistance [p.u]	Reactance [p.u]	S_l^{max} [MVA]
1	2	NaN	0.0146	1275
1	3	NaN	0.2253	775
1	5	NaN	0.0907	900
2	4	NaN	0.1356	775
2	6	NaN	0.205	775
3	9	NaN	0.1271	775
3	24	NaN	0.084	300
4	9	NaN	0.111	775
5	10	NaN	0.094	950
6	10	NaN	0.0642	900
7	8	NaN	0.0652	1250
8	9	NaN	0.1762	975
8	10	NaN	0.1762	975
9	11	NaN	0.084	70
9	12	NaN	0.084	70
10	11	NaN	0.084	200
10	12	NaN	0.084	200
11	13	NaN	0.0488	200
11	14	NaN	0.0426	800
12	13	NaN	0.0488	100
12	23	NaN	0.0985	800

13	23	NaN	0.0884	180
14	16	NaN	0.0594	450
15	16	NaN	0.0172	600
15	21	NaN	0.0249	100
15	24	NaN	0.0529	900
16	17	NaN	0.0263	500
16	19	NaN	0.0234	500
17	18	NaN	0.0143	500
17	22	NaN	0.0269	400
18	21	NaN	0.0132	250
19	20	NaN	0.0203	200
20	23	NaN	0.0112	200
21	22	NaN	0.0692	500
15	25	0.0001	0.00003	800
25	26	0.0001	0.00003	800
26	27	0.0001	0.00003	840
27	28	0.0001	0.00003	880
28	29	0.0001	0.00003	85.8
6	30	0.0001	0.00003	500
30	31	0.0001	0.00003	500
31	32	0.0001	0.00003	400
32	33	0.0001	0.00003	350
33	34	0.0001	0.00003	200
19	35	0.0001	0.00003	400
35	36	0.0001	0.00003	290
36	37	0.0001	0.00003	290
37	38	0.0001	0.00003	290
38	39	0.0001	0.00003	165
13	40	0.0001	0.00003	850
40	41	0.0001	0.00003	855
41	42	0.0001	0.00003	890
42	43	0.0001	0.00003	710
43	44	0.0001	0.00003	140
18	45	0.0001	0.00003	557
45	46	0.0001	0.00003	350
46	47	0.0001	0.00003	355

Table F.11: Line parameters for the 24-bus case study with 5 added DSOs.

Demand	Location in network	π_d^{DA}	$\pi_d^{\uparrow}$	$\pi_d^{\downarrow}$	$\overline{P}_d$
D_1	node 1	19.1	11	8	158.4
D_2	node 2	19	13	8	178.2
D_3	node 3	18	10	25	75.9
D_4	node 4	18.5	11.5	8	85.8
D_5	node 5	19.2	17	8	82.5
D_6	node 7	18	17	8	145.2
D_7	node 8	19.25	14	8	198.0
D_8	node 9	19	11	8	300.3
D_9	node 10	18.4	21	8	323.4
D_{10}	node 14	19.9	8	5	125.4
D_{11}	node 16	19.2	15	5.9	148.5
D_{12}	node 20	19.3	16	5	445.5
D_{13}	DSO1	22	29	3	198.0
D_{14}	DSO1	23	21.5	4.3	214.5
D_{15}	DSO1	23	20	1	83.8
D_{16}	DSO2	20	21	5.2	198.0
D_{17}	DSO2	21	24.3	8	198.0
D_{18}	DSO2	21	21.1	8	57.4
D_{19}	DSO3	21	21	4	98.0
D_{20}	DSO3	21.2	21.2	2.2	198.0
D_{21}	DSO3	21.3	22.4	3	43.2
D_{22}	DSO4	20	21.1	2.4	201.3
D_{23}	DSO4	20	21.4	5	201.3
D_{24}	DSO4	20	20.4	3.2	11.3
D_{25}	DSO5	20	22	1.5	26.0
D_{26}	DSO5	20	22.7	4	193.0
D_{27}	node 3	30	10	8	39.9

Table F.9: Demand bid prices for the large 24-bus case study.

Wind-generator	Location in network	π^R	$\pi^{\uparrow R}$	$\pi^{\downarrow R}$
W_1	node 3	0	2.2	30.5
W_2	node 5	0	2.1	30.7
W_3	node 7	0	2.4	30.4
W_4	node 16	0	4.1	30.2
W_5	node 21	0	3.2	30
W_6	node 23	0	2.9	30.2
W_7	DSO3	0	5.1	30.5

Table F.10: Wind generator offer prices for the large 24-bus case study.