Supplementary Material

Strategic interactions between liquefied natural gas and domestic gas markets: A bilevel model

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Description: This supplementary information file provides the mathematical models for all the models used in the scenario analysis described in the paper.

1. Mathematical models for scenario analysis

1.1. Cooperative Scenario

$$\begin{aligned}\max \ &\sum_{j\in\mathcal{M}} p_j^{\mathrm{LNG}} d_j^{\mathrm{LNG}} + \sum_{j\in\mathcal{N}} p_j^{\mathrm{spot}} d_j^{\mathrm{spot}} - \sum_{j\in\mathcal{N}} C_j^{\mathrm{LNGfixed}} z_j - \sum_{j\in\mathcal{N}} C_j^{\mathrm{LNGunit}} \mu_j - \sum_{j\in\mathcal{N}} C_j^{\mathrm{liq}} \nu_j \\ &- \sum_{j\in\mathcal{N}} C_j^{\mathrm{unit}} Q_j - \sum_{j\in\mathcal{N}} {C_a}_j^{\mathrm{prod}} q_j^2 - \sum_{j\in\mathcal{N}} {C_b}_j^{\mathrm{prod}} q_j - \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{M}} C_{ij}^{\mathrm{LNGship}} l_{ij} - \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}} C_{ij}^{\mathrm{pipe}} x_{ij} \\ &- \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}} C_{ij}^{\mathrm{ship}} f_{ij} \end{aligned} \tag{1a}$$

subject to

$$\sum_{i\in\mathcal{M}} l_{ji} \le (1-\eta_j)\ \nu_j \qquad \forall \quad j\in\mathcal{N} \tag{1b}$$

$$\nu_j \le \mu_j \qquad \forall \quad j\in\mathcal{N} \tag{1c}$$

$$\mu_j \le K_j^{\mathrm{LNG}} z_j \qquad \forall \quad j\in\mathcal{N} \tag{1d}$$

$$q_j \le Q_j \qquad \forall \quad j\in\mathcal{N} \tag{1e}$$

$$Q_j \le K_j \qquad \forall \quad j\in\mathcal{N} \tag{1f}$$

$$f_{ij} \le A_{ij} x_{ij} \qquad \forall \quad i,j\in\mathcal{N} \tag{1g}$$

$$\sum_{i\in\mathcal{N}} l_{ij} = d_j^{\mathrm{LNG}} \qquad \forall \quad j\in\mathcal{M} \tag{1h}$$

$$\sum_{i\in\mathcal{N}} f_{ij} + q_j = \sum_{i\in\mathcal{N}} f_{ji} + d_j^{\mathrm{spot}} + \nu_j \qquad \forall \quad j\in\mathcal{N} \tag{1i}$$

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$$d_j^{\text{LNG}} = a_j^{\text{LNG}} - b_j^{\text{LNG}} p_j^{\text{LNG}} \qquad \forall \quad j \in \mathcal{M} \tag{1j}$$

$$d_j^{\text{spot}} = a_j^{\text{spot}} - b_j^{\text{spot}} p_j^{\text{spot}} \qquad \forall \quad j \in \mathcal{N} \tag{1k}$$

$$z_j \in \{0, 1\} \qquad \forall \quad j \in \mathcal{N} \tag{1l}$$

$$\nu_j, \mu_j, q_j, Q_j, p_j^{\text{LNG}}, p_j^{\text{spot}}, d_j^{\text{LNG}}, d_j^{\text{spot}} \in \mathbb{R}_+ \qquad \forall \quad j \in \mathcal{N} \tag{1m}$$

$$l_{ij}, x_{ij}, f_{ij} \in \mathbb{R}_+ \qquad \forall \quad i \in \mathcal{N}, j \in \mathcal{M} \tag{1n}$$

1.2. No LNG Scenario

$$\begin{aligned} \max \sum_{j \in \mathcal{N}} p_j^{\text{spot}} d_j^{\text{spot}} - \sum_{j \in \mathcal{N}} C_j^{\text{unit}} Q_j - \sum_{j \in \mathcal{N}} C_{a_j}^{\text{prod}} q_j^2 - \sum_{j \in \mathcal{N}} C_{b_j}^{\text{prod}} q_j - \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{N}} C_{ij}^{\text{pipe}} x_{ij} \\ - \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{N}} C_{ij}^{\text{ship}} f_{ij} \end{aligned} \tag{2a}$$

subject to

$$\sum_{i \in \mathcal{N}} f_{ij} + q_j = \sum_{i \in \mathcal{N}} f_{ji} + d_j^{\text{spot}} \qquad \forall \quad j \in \mathcal{N} \tag{2b}$$

$$q_j \leq Q_j \qquad \forall \quad j \in \mathcal{N} \tag{2c}$$

$$Q_j \leq K_j \qquad \forall \quad j \in \mathcal{N} \tag{2d}$$

$$f_{ij} \leq A_{ij} x_{ij} \qquad \forall \quad i, j \in \mathcal{N} \tag{2e}$$

$$d_j^{\text{spot}} = a_j^{\text{spot}} - b_j^{\text{spot}} p_j^{\text{spot}} \qquad \forall \quad j \in \mathcal{N} \tag{2f}$$

$$q_j, Q_j, p_j^{\text{spot}}, d_j^{\text{spot}} \in \mathbb{R}_+ \qquad \forall \quad j \in \mathcal{N} \tag{2g}$$

$$x_{ij}, f_{ij} \in \mathbb{R}_+ \qquad \forall \quad i, j \in \mathcal{N} \tag{2h}$$

1.3. Naïve LNG Scenario

In the Naïve LNG scenario, the LNG operator (leader) makes decisions assuming that gas procurement prices will be the same as the spot prices in the solution to the No LNG scenario. This scenario is solved in two parts. In part 1, we solve only the leader's problem, where the LNG operator expects to see the same gas prices as seen from the No LNG scenario described in Section 1.2, i.e., $p_j^{\nu} = p_j^{\text{spot}} \ \forall \ j \in \mathcal{N}$. The LNG operator makes the LNG capacity investment decisions ($z_j, \mu_j \ \forall \ j \in \mathcal{N}$) assuming the gas prices ($p_j^{\nu} \ \forall \ j \in \mathcal{N}$) to be a parameter rather than a variable.

$$\begin{aligned} \max \sum_{j \in \mathcal{M}} p_j^{\text{LNG}} d_j^{\text{LNG}} - \sum_{j \in \mathcal{N}} p_j^{\nu} \nu_j - \sum_{j \in \mathcal{N}} C_j^{\text{LNGfixed}} z_j - \sum_{j \in \mathcal{N}} C_j^{\text{LNGunit}} \mu_j - \sum_{j \in \mathcal{N}} C_j^{\text{liq}} \nu_j \\ - \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{M}} C_{ij}^{\text{LNGship}} l_{ij} \end{aligned} \tag{3a}$$

subject to

$$\sum_{i\in\mathcal{M}} l_{ji} \le (1-\eta_j)\ \nu_j \qquad \forall \quad j\in\mathcal{N} \tag{3b}$$

$$\nu_j \le \mu_j \qquad \forall \quad j\in\mathcal{N} \tag{3c}$$

$$\mu_j \le K_j^{\mathrm{LNG}} z_j \qquad \forall \quad j\in\mathcal{N} \tag{3d}$$

$$\sum_{i\in\mathcal{N}} l_{ij} = d_j^{\mathrm{LNG}} \qquad \forall \quad j\in\mathcal{M} \tag{3e}$$

$$\nu_j = a_j^{\nu} - b_j^{\nu} p_j^{\nu} \qquad \forall \quad j\in\mathcal{N} \tag{3f}$$

$$d_j^{\mathrm{LNG}} = a_j^{\mathrm{LNG}} - b_j^{\mathrm{LNG}} p_j^{\mathrm{LNG}} \qquad \forall \quad j\in\mathcal{M} \tag{3g}$$

$$z_j \in \{0,1\} \qquad \forall \quad j\in\mathcal{N} \tag{3h}$$

$$p_j^{\mathrm{LNG}}, \nu_j, \mu_j, d_j^{\mathrm{LNG}} \in \mathbb{R}_+ \qquad \forall \quad j\in\mathcal{N} \tag{3i}$$

$$l_{ij} \in \mathbb{R}_+ \qquad \forall \quad i\in\mathcal{N}, j\in\mathcal{M} \tag{3j}$$

Once the LNG capacity investment decisions are made by the LNG operator, the demand for gas will be higher at the locations where LNG facilities are opened by the LNG operator. The NG producer in this case now has the ability to fix the gas prices p^{spot} and p^{ν} so as to maximize his profits. For part 2, we solve a bilevel problem similar to the one described in Section 3 of the paper but with the variables associated with the capacity investment decisions (z_j and μ_j) now being parameters.

1.4. Existing Pipeline Network Scenario

This is the same as the Bilevel scenario, except it assumes that a pipeline network already exists to transmit gas across regions. For this scenario, the upper–level problem is the same as described in Section 3.2.1 of the paper. We assume that the NG producer has access to a pipeline network with pre-defined capacities, represented by K^{pipe}. The lower–level problem is as follows:

$$\max \sum_{j\in\mathcal{N}} p_j^{\mathrm{spot}} d_j^{\mathrm{spot}} + \sum_{j\in\mathcal{N}} p_j^{\nu}\nu_j - \sum_{j\in\mathcal{N}} C_j^{\mathrm{unit}} Q_j - \sum_{j\in\mathcal{N}} C_{a_j}^{\mathrm{prod}} q_j^2 - \sum_{j\in\mathcal{N}} C_{b_j}^{\mathrm{prod}} q_j - \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}} C_{ij}^{\mathrm{ship}} f_{ij} \tag{4a}$$

subject to

$$\sum_{i\in\mathcal{N}} f_{ij} + q_j = \sum_{i\in\mathcal{N}} f_{ji} + d_j^{\mathrm{spot}} + \nu_j \qquad \forall \quad j\in\mathcal{N} \qquad (\lambda_j) \tag{4b}$$

$$q_j \le Q_j \qquad \forall \quad j\in\mathcal{N} \qquad (\theta_j) \tag{4c}$$

$$Q_j \le K_j \qquad \forall \quad j\in\mathcal{N} \qquad (\alpha_j) \tag{4d}$$

$$f_{ij} \leq K_{ij}^{\text{pipe}} \qquad \forall \quad i,j \in \mathcal{N} \qquad (\beta_{ij}) \tag{4e}$$

$$d_j^{\text{spot}} = a_j^{\text{spot}} - b_j^{\text{spot}} p_j^{\text{spot}} \qquad \forall \quad j \in \mathcal{N} \qquad (\kappa_j) \tag{4f}$$

$$\nu_j = a_j^{\nu} - b_j^{\nu} p_j^{\nu} \qquad \forall \quad j \in \mathcal{N} \qquad (\tau_j) \tag{4g}$$

$$q_j, Q_j, p_j^{\text{spot}}, p_j^{\nu}, d_j^{\text{spot}} \in \mathbb{R}_+ \qquad \forall \quad j \in \mathcal{N} \tag{4h}$$

$$f_{ij} \in \mathbb{R}_+ \qquad \forall \quad i,j \in \mathcal{N} \tag{4i}$$

The reformulated MPCC in this case becomes:

$$\begin{aligned} \max \sum_{j \in \mathcal{M}} a_j^{\text{LNG}} p_j^{\text{LNG}} - \sum_{j \in \mathcal{M}} b_j^{\text{LNG}} (p_j^{\text{LNG}})^2 - \sum_{j \in \mathcal{N}} a_j^{\nu} p_j^{\nu} + \sum_{j \in \mathcal{N}} u_j - \sum_{j \in \mathcal{N}} C_j^{\text{LNGfixed}} z_j \\ - \sum_{j \in \mathcal{N}} C_j^{\text{LNGfixed}} \mu_j - \sum_{j \in \mathcal{N}} C_j^{\text{liq}} \ \nu_j - \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{M}} C_{ij}^{\text{LNGship}} l_{ij} \end{aligned} \tag{5a}$$

$$\text{s.t.} \quad u_j \leq a_{sj}^{\text{pw}} + b_{sj}^{\text{pw}} p_j^{\nu} \qquad \forall \quad s \in \mathcal{S}, j \in \mathcal{N} \tag{5b}$$

$$u_j \geq a_{sj}^{\text{pw}} + b_{sj}^{\text{pw}} p_j^{\nu} - M(1 - \xi_{sj}) \qquad \forall \quad s \in \mathcal{S}, j \in \mathcal{N} \tag{5c}$$

$$\sum_{s \in \mathcal{S}} \xi_{sj} = 1 \qquad \forall \quad j \in \mathcal{N} \tag{5d}$$

$$\sum_{i \in \mathcal{M}} l_{ji} \leq (1 - \eta_j) \ \nu_j \qquad \forall \quad j \in \mathcal{N} \tag{5e}$$

$$\nu_j \leq \mu_j \qquad \forall \quad j \in \mathcal{N} \tag{5f}$$

$$\mu_j \leq K_j^{\text{LNG}} z_j \qquad \forall \quad j \in \mathcal{N} \tag{5g}$$

$$\sum_{i \in \mathcal{N}} l_{ij} = a_j^{\text{LNG}} - b_j^{\text{LNG}} p_j^{\text{LNG}} \qquad \forall \quad j \in \mathcal{N} \tag{5h}$$

$$0 \leq p_j^{\text{spot}} \perp -d_j^{\text{spot}} + b_j^{\text{spot}} \kappa_j \geq 0 \qquad \forall \quad j \in \mathcal{N} \tag{5i}$$

$$0 \leq p_j^{\nu} \perp -\nu_j + b_j^{\nu} \tau_j \geq 0 \qquad \forall \quad j \in \mathcal{N} \tag{5j}$$

$$0 \leq d_j^{\text{spot}} \perp -p_j^{\text{spot}} + \lambda_j + \kappa_j \geq 0 \qquad \forall \quad j \in \mathcal{N} \tag{5k}$$

$$0 \leq Q_j \perp C_j^{\text{unit}} - \theta_j + \alpha_j \geq 0 \qquad \forall \quad j \in \mathcal{N} \tag{5l}$$

$$0 \leq q_j \perp 2 \ C_{a_j}^{\text{prod}} q_j + C_{b_j}^{\text{prod}} + \theta_j - \lambda_j \geq 0 \qquad \forall \quad j \in \mathcal{N} \tag{5m}$$

$$0 \leq f_{ij} \perp C_{ij}^{\text{ship}} + \lambda_i - \lambda_j + \beta_{ij} \geq 0 \qquad \forall \quad j \in \mathcal{N} \tag{5n}$$

$$0 \leq \theta_j \perp Q_j - q_j \geq 0 \qquad \forall \quad j \in \mathcal{N} \tag{5o}$$

$$0 \leq \alpha_j \perp K_j - Q_j \geq 0 \qquad \forall \quad j \in \mathcal{N} \tag{5p}$$

$$0 \leq \beta_{ij} \perp A_{ij} K_{ij}^{\text{pipe}} - f_{ij} \geq 0 \qquad \forall \quad j \in \mathcal{N} \tag{5q}$$

$$\sum_{i \in \mathcal{N}} f_{ij} + q_j = \sum_{i \in \mathcal{N}} f_{ji} + d_j^{\text{spot}} + \nu_j \qquad \forall \quad j \in \mathcal{N} \tag{5r}$$

$$d_j^{\text{spot}} = a_j^{\text{spot}} - b_j^{\text{spot}} p_j^{\text{spot}} \qquad \forall \quad j \in \mathcal{N} \tag{5s}$$

$$\nu_j = a_j^{\nu} - b_j^{\nu} p_j^{\nu} \qquad \forall \quad j \in \mathcal{N} \tag{5t}$$

$$z_j \in \{0, 1\} \qquad \forall \quad j \in \mathcal{N} \tag{5u}$$

$$\xi_{sj} \in \{0, 1\} \qquad \forall \quad s \in \mathcal{S}, j \in \mathcal{N} \tag{5v}$$

$$l_{ij}, x_{ij}, f_{ij}, \beta_{ij} \in \mathbb{R}_+ \qquad \forall \quad i, j \in \mathcal{N} \tag{5w}$$

$$\nu_j, \mu_j, p_j^{\text{LNG}}, p_j^{\text{spot}}, p_j^{\nu}, q_j, Q_j, d_j^{\text{spot}}, \theta_j, \alpha_j \in \mathbb{R}_+ \qquad \forall \quad j \in \mathcal{N} \tag{5x}$$

$$\lambda_j, \tau_j, \kappa_j, u_j \in \mathbb{R} \qquad \forall \quad j \in \mathcal{N} \tag{5y}$$