operations research
QUANTITATIVE INFRASTRUCTURE SYSTEM MODELING

A Multi-Commodity Partial Equilibrium Model

Imperfect Competition in Future Global Hydrogen Markets

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Agenda

Motivation

- Some hydrogen strategies of traditional fuel-importing regions feature the assumption that a substantial part of demand be imported from currently non-existing global markets
  - E.g. BMWi (2020) and BMWK (2023), with 50–70 % of the 95–130 TW h by 2030
  - Or the REPowerEU plan (EC 2022) with 10 Mt of domestic production and 10 Mt of imports by 2030
  - Japan also aims for the establishment of international value chains (METI 2023)

Motivation

- Hence, some techno-economic literature investigates procurement and shipping cost
  - Often, it is assumed that prices towards demand side are formed in a cost-reflective fashion.
  - In the traditional energy world, this is rarely the case
- Only few works investigate strategic behavior on a global scale (e.g. Ikonnikova, Scanlon, and Berdysheva 2023)

Motivation

- Several characteristics indicate potential for strategic behavior:
  - Limited time to develop sufficient human and financial capacity to realize large-scale deployment
  - High capital intensity of investment as barrier to market entry
    - Many regions with high renewable potentials have less dependable institutional frameworks
  - Threat of moving towards more competitive pricing in the long term
  - Price elasticity of demand
    - Limited options for substitution
    - Move away from fossil fuels incentivizes hydrogen use
    - Used where other options are expensive or unavailable (e.g. electrification)
  - Subsidized long-term contracting vs competitive spot markets

Agenda

Model Overview

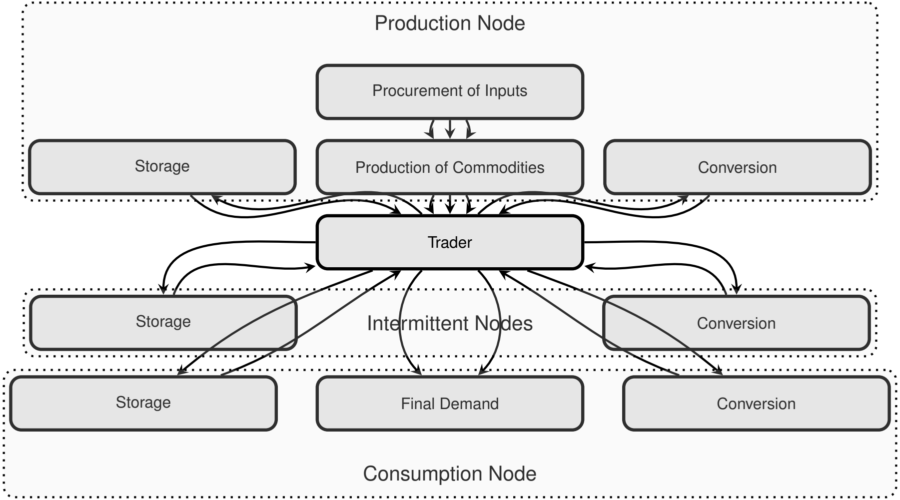


Figure: Model Overview.

Agenda

Producer Problem

- Maximize discounted profits from selling commodities to traders
  - Piece-wise quadratic input operational cost
  - Unit expansion cost for production and input capacities
- Such that:
  - Sufficient inputs for production are procured
  - Inputs are constrained by the sum of exogenous and invested capacity, accounted for availability
  - Production is constrained by the sum of exogenous and invested capacity
  - Annual production investment is limited
  - Active input procurement capacities are limited

$$\max_{\substack{q^I_{pibmy},\\ q^{P\to T}_{pcomy},\\ \Delta^I_{piby},\\ \Delta^P_{pcoy}}} \sum_{y\in\mathcal{Y}} r_y \Bigg[\sum_{m\in\mathcal{M}} d_m \Bigg(\sum_{o\in\mathcal{O}} \sum_{c\in\mathcal{C}} \left(\pi^P_{n(p)comy} - c^P_{pcoy}\right) q^{P\to T}_{pcomy} - \sum_{i\in\mathcal{I}} \sum_{b\in\mathcal{IOB}} \left(c^{I_l}_{pibmy} q^I_{pibmy} + \frac{1}{2} c^{I_q}_{pibmy} \left(q^I_{pibmy}\right)^2 \right) \Bigg) - \sum_{i\in\mathcal{I}} \sum_{b\in\mathcal{IOB}} \frac{1}{\|\Delta\|_y} c^{\Delta^I}_{piby} \Delta^I_{piby} - \sum_{c\in\mathcal{C}} \sum_{o\in\mathcal{O}} \frac{1}{\|\Delta\|_y} c^{\Delta P}_{pcoy} \Delta^P_{pcoy} \Bigg]$$

$$\text{s.t.} \quad \sum_{o\in\mathcal{O}} \sum_{c\in\mathcal{C}} fi^P_{cio} q^{P\to T}_{pcomy} \le \sum_{b\in\mathcal{IOB}} q^I_{pibmy} \qquad \forall i \in \mathcal{I}, m \in \mathcal{M}, y \in \mathcal{Y} \quad (\phi^P_{pimy})$$

$$q^I_{pibmy} \le av^I_{pibm} \left(\Lambda^I_{piby} + \sum_{y'\in\mathcal{Y} | (y - L^I_i \le y' < y)} \Delta^I_{piby} \right) \qquad \forall i \in \mathcal{I}, b \in \mathcal{IOB}, m \in \mathcal{M}, y \in \mathcal{Y} \quad (\Lambda^I_{piby})$$

$$q^{P\to T}_{pcomy} \le \left(\Lambda^P_{pcoy} + \sum_{y'\in\mathcal{Y} | (y - L^P_{co} \le y' < y)} \Delta^P_{pcoy} \right) \qquad \forall c \in \mathcal{C}, \forall o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y} \quad (\lambda^P_{pcomy})$$

$$\Delta^P_{pcoy} \le \Omega^P_{pcoy} \qquad \forall c \in \mathcal{C}, o \in \mathcal{O}, y \in \mathcal{Y} \quad (\omega^P_{pcoy})$$

$$\sum_{y'\in\mathcal{Y} | (y - L^I_i \le y' < y)} \Delta^I_{piby'} \le \Omega^I_{piby} \qquad \forall i \in \mathcal{I}, b \in \mathcal{IOB}, y \in \mathcal{Y} \quad (\omega^I_{piby})$$

$$q^I_{pibmy}, q^{P\to T}_{pcomy}, \Delta^I_{piby}, \Delta^P_{pcoy} \ge 0$$

Trader Problem

- Maximize discounted profits from interacting with other players
  - Demand
  - Conversion
  - Storage
  - Transport
  - Producers
- Such that:
  - Nodal mass balances check out
    - Sales, and outgoing flows to storage, conversion and transport
    - Reception from producers, converters, transport and storage
  - Trade limitations are accounted for

$$\max_{\substack{q^{T\to D}_{tncbomy},\\ q^{T\leftarrow P}_{tncomy},\\ q^{T\to V}_{tncomy},\\ q^{T\leftarrow V}_{tncomy},\\ q^{T\to S}_{tncomy},\\ q^{T\leftarrow S}_{tncomy},\\ q^{T}_{tacomy}}} \sum_{y\in\mathcal{Y}} r_y \sum_{m\in\mathcal{M}} d_m \sum_{o\in\mathcal{O}} \sum_{c\in\mathcal{C}} \left[\begin{aligned} &\sum_{n\in\mathcal{N}} \left(\begin{aligned} &\mathbb{1}^{NC}_{tnc} \cdot \sum_{b\in\mathcal{DSB}} \tilde{P}^{T\to D}_{ncbmy}\left(Q^{T\to D}_{ncbmy}\right) \cdot q^{T\to D}_{tncbomy} \\ &+ \left(1-\mathbb{1}^{NC}_{tnc}\right) \cdot \sum_{b\in\mathcal{DSB}} \pi^{T\to D}_{ncbmy} \cdot q^{T\to D}_{tncbomy} \end{aligned} \right) \\ &+ \sum_{n\in\mathcal{N}} \left(\pi^{T\to V}_{tncomy}\right) q^{T\to V}_{tncomy} \\ &- \sum_{n\in\mathcal{N}} \left(\pi^{V\to T}_{tncomy}\right) q^{T\leftarrow V}_{tncomy} \\ &+ \sum_{n\in\mathcal{N}} \left(\pi^{T\to S}_{tncomy}\right) q^{T\to S}_{tncomy} \\ &- \sum_{n\in\mathcal{N}} \left(\pi^{S\to T}_{tncomy}\right) q^{T\leftarrow S}_{tncomy} \\ &- \sum_{a\in\mathcal{A}|(a,c)\in\mathcal{AC}} \left(\pi^{A}_{acmy}\right) q^{T}_{tacomy} \\ &- \sum_{n\in\mathcal{N}_p(t)} \left(\pi^{P}_{ncomy}\right) q^{T\leftarrow P}_{tncomy} \end{aligned} \right]$$

$$\text{s.t.} \left(\begin{aligned} &\sum_{a\in\mathcal{A}_s(n)|(a,c)\in\mathcal{AC}} \left(1+l^{A}_{ac}\right) q^{T}_{tacomy} \\ &+ \sum_{b\in\mathcal{DSB}} q^{T\to D}_{tncbomy} \\ &+ q^{T\to V}_{tncomy} \\ &+ q^{T\to S}_{tncomy} \end{aligned} \right) \le \left(\begin{aligned} &\sum_{a\in\mathcal{A}_e(n)|(a,c)\in\mathcal{AC}} q^{T}_{tacomy} \\ &+ \sum_{n\in\mathcal{N}_p(t)} q^{T\leftarrow P}_{tncomy} \\ &+ q^{T\leftarrow V}_{tncomy} \\ &+ q^{T\leftarrow S}_{tncomy} \end{aligned} \right) \quad \begin{aligned} &\forall n\in\mathcal{N}, c\in\mathcal{C}, \\ &o\in\mathcal{O}, m\in\mathcal{M}, \\ &y\in\mathcal{Y} \end{aligned} \quad \left(\phi^{T}_{tncomy}\right)$$

$$\sum_{m\in\mathcal{M}} d_m \sum_{b\in\mathcal{DSB}} q^{T\to D}_{tncbomy} \le \Lambda^{T}_{tncoy} \quad \begin{aligned} &\forall n\in\mathcal{N}, c\in\mathcal{C}, \\ &o\in\mathcal{O}, y\in\mathcal{Y} \end{aligned} \quad \left(\lambda^{T}_{tncoy}\right)$$

$$q^{T\to D}_{tncbomy}, q^{T\leftarrow P}_{tncomy}, q^{T\to V}_{tncomy}, q^{T\leftarrow V}_{tncomy}, q^{T\to S}_{tncomy}, q^{T\leftarrow S}_{tncomy}, q^{T}_{tacomy} \ge 0$$

Converter Problem

- Maximize discounted profits from converting commodities on behalf of traders
  - Revenues from conversion
  - Unit capacity expansion cost
  - Cost of repurposing legacy conversion infrastructure
- Such that:
  - Total converted quantities do not exceed active capacity
    - Exogenous capacity
    - Endogenous investment
    - Net of repurposed capacity

$$\max_{\substack{q^{V}_{vtcdomy},\\ \Delta^{V}_{vcc'y},\\ \Delta^{RV}_{vrr'cc'y}}} \sum_{y\in\mathcal{Y}} r_y \left[\sum_{(c,c')\in\mathcal{VT}} \left(\sum_{t\in\mathcal{T}} \sum_{o\in\mathcal{O}} \sum_{m\in\mathcal{M}} d_m \left(\pi^{V\to T}_{tnc'omy} - fi^{V}_{cc'} \pi^{T\to V}_{tncomy} - c^{V}_{vcc'y}\right) q^{V}_{vtcc'omy} - \frac{1}{\|\Delta\|_y} c^{\Delta V}_{vcc'y} \Delta^{V}_{vcc'y} \right) - \frac{1}{\|\Delta\|_y} \sum_{((r,r'),(cc'))\in\mathcal{RV}} c^{\Delta RV}_{vrr'cc'y} \Delta^{RV}_{vrr'cc'y} \right]$$

$$\text{s.t.} \quad \sum_{o\in\mathcal{O}} \sum_{t\in\mathcal{T}} q^{V}_{vtcc'omy} \leq \left(\Lambda^{V}_{vcc'y} + \sum_{y'\in\mathcal{Y}|y-L^{V}_{cc'}\leq y'<y} \Delta^{V}_{vcc'y} + \sum_{(r,r')|((r,r'),(cc'))\in\mathcal{RV}} \sum_{y'\in\mathcal{Y}|y-L^{V}_{cc'}\leq y'<y} f^{RV}_{rr'cc'} \Delta^{RV}_{vrr'cc'y} - \sum_{(r,r')|((cc'),(r,r'))\in\mathcal{RV}} \sum_{y'\in\mathcal{Y}|y'<y} \Delta^{RV}_{vcc'rr'y} \right) \quad \forall m\in\mathcal{M}, y\in\mathcal{Y}, (c,c')\in\mathcal{VT} \quad (\lambda^{V}_{vcc'my})$$

$$q^{V}_{vtcc'omy}, \Delta^{V}_{vcc'y}, \Delta^{RV}_{vrr'cc'y} \geq 0$$

Transmission System Operator Problem

- Maximize discounted profits from auctioning capacity
  - Revenues from transporting
  - Investment cost
  - Repurposing cost
- Such that:
  - Auctioned capacity does not exceed existing capacity
    - Exogenous capacity
    - Endogenous investment
    - Net of repurposed capacity
  - Capacity expansion is symmetric
  - Repurposing is symmetric

$$\max_{q^A_{acmy},\,\Delta^A_{acy},\,\Delta^{RA}_{arcy}} \sum_{y\in\mathcal{Y}} r_y \sum_{a\in\mathcal{A}} \left[\sum_{c\in\mathcal{C}|(a,c)\in\mathcal{AC}} \left(\sum_{m\in\mathcal{M}} d_m \left(\pi^A_{acmy} - c^A_{acy}\right) q^A_{acmy} - \frac{1}{\|\Delta\|_y} \frac{1}{2} c^{\Delta A}_{acy} \Delta^A_{acy} \right) - \frac{1}{\|\Delta\|_y} \sum_{(r,c)\in\mathcal{RA}|(a,r)\in\mathcal{AC}} \frac{1}{2} c^{\Delta^{RA}}_{arcy} \Delta^{RA}_{arcy} \right]$$

$$\text{s.t.} \quad q^A_{acmy} \le \begin{pmatrix} \Lambda^A_{acy} \\ + \sum_{y'\in\mathcal{Y}|y-L^A_c\le y'<y} \Delta^A_{acy} \\ + \sum_{r|(r,c)\in\mathcal{RA}} \sum_{y'\in\mathcal{Y}|y-L^A_c\le y'<y} f^{RA}_{rc} \Delta^{RA}_{arcy} \\ - \sum_{r|(c,r)\in\mathcal{RA}} \sum_{y'\in\mathcal{Y}|y'<y} \Delta^{RA}_{acry} \end{pmatrix} \quad \forall (a,c)\in\mathcal{AC},\ m\in\mathcal{M}, y\in\mathcal{Y} \quad (\lambda^A_{acmy})$$

$$\Delta^A_{acy} = \Delta^A_{a^{-1}(a)cy} \quad \forall (a,c)\in\mathcal{AC},\ y\in\mathcal{Y} \quad (\delta^A_{acy})$$

$$\Delta^{RA}_{arcy} = \Delta^{RA}_{a^{-1}(a)rcy} \quad \forall a\in\mathcal{A}, (r,c)\in\mathcal{RA},\ (a,r)\in\mathcal{AC},\ y\in\mathcal{Y} \quad (\delta^{RA}_{arcy})$$

$$q^A_{acmy}, \Delta^A_{acy}, \Delta^{RA}_{arcy} \ge 0$$

Storage System Operator Problem

- Maximize discounted profits from storing commodities on behalf of traders
  - Revenues from acquiring and reselling
  - Capacity expansion cost
  - Repurposing cost
- Such that:
  - Stored volumes do not exceed active capacity
    - Exogenous capacity
    - Capacity investments
    - Net repurposing
  - Intertemporal mass balance is accounted
  - Active capacity does not exceed physical limits

$$\max_{\substack{q^S_{stcomy},\\ q^{S_{in}}_{stcomy},\\ q^{S_{out}}_{stcomy},\\ \Delta^S_{scy},\\ \Delta^{RS}_{srcy}}} \sum_{y\in\mathcal{Y}} r_y \left[\sum_{c\in\mathcal{C}} \left(\sum_{m\in\mathcal{M}} \sum_{t\in\mathcal{T}} \sum_{o\in\mathcal{O}} d_m \left[\begin{array}{l} \left(\pi^{S\to T}_{tn(s)comy} - c^{S_{out}}_{scy}\right) q^{S_{out}}_{stcomy} \\ - \left(\pi^{T\to S}_{tn(s)comy} + c^{S_{in}}_{scy}\right) q^{S_{in}}_{stcomy} \end{array} \right] - \frac{1}{\|\Delta\|_y} c^{\Delta S}_{scy} \Delta^S_{scy} \right) - \frac{1}{\|\Delta\|_y} \sum_{(r,c)\in\mathcal{RS}} c^{\Delta^{RS}}_{srcy} \Delta^{RS}_{srcy} \right]$$

$$\text{s.t.} \quad \sum_{o\in\mathcal{O}} \sum_{t\in\mathcal{T}} q^S_{stcomy} \le \left(\begin{array}{l} \Lambda^S_{scy} \\ + \sum_{y'\in\mathcal{Y}|y-L^S_c\le y'<y} \Delta^S_{scy} \\ + \sum_{r|(r,c)\in\mathcal{RS}} \sum_{y'\in\mathcal{Y}|y-L^S_c\le y'<y} f^{RS}_{rc} \Delta^{RS}_{srcy} \\ - \sum_{r|(c,r)\in\mathcal{RS}} \sum_{y'\in\mathcal{Y}|y'<y} \Delta^{RS}_{scry} \end{array} \right) \qquad \forall c\in\mathcal{C}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\lambda^S_{scmy})$$

$$\left(1 - l^S_{cmm^+(m)}\right) \cdot \left[\begin{array}{l} q^S_{stcomy} \\ + d_m \left(q^{S_{in}}_{stcomy} - q^{S_{out}}_{stcomy}\right) \end{array} \right] \ge q^S_{stcom^+(m)y} \qquad \forall t\in\mathcal{T}, c\in\mathcal{C}, o\in\mathcal{O}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\phi^S_{stcomy})$$

$$\left(\begin{array}{l} \sum_{y'\in\mathcal{Y}|y-L^S_c\le y'<y} \Delta^S_{scy} \\ + \sum_{r|(r,c)\in\mathcal{RS}} \sum_{y'\in\mathcal{Y}|y-L^S_c\le y'<y} f^{RS}_{rc} \Delta^{RS}_{srcy} \\ - \sum_{r|(c,r)\in\mathcal{RS}} \sum_{y'\in\mathcal{Y}|y'<y} \Delta^{RS}_{scry} \end{array} \right) \le \Omega^S_{scy} \qquad \forall c\in\mathcal{C}, y\in\mathcal{Y} \quad (\omega^S_{scy})$$

$$q^S_{stcomy}, q^{S_{in}}_{stcomy}, q^{S_{out}}_{stcomy}, \Delta^S_{scy}, \Delta^{RS}_{srcy} \ge 0$$

Market Clearing Conditions

- Connect individual problems between
  - Producer and trader
  - Trader and demand
  - Trader to converter
  - Trader from converter
  - Trader and transport
  - Trader to storage
  - Trader from storage

$$\left[q^{P\rightarrow T}_{p(n)comy} - q^{T\leftarrow P}_{t(n)ncomy}\right] \geq 0 \perp \pi^{P}_{ncomy} \geq 0 \qquad \forall n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\pi^{T\rightarrow D}_{ncbmy} - \tilde{P}^{T\rightarrow D}_{ncbmy}\left(\sum_{o\in\mathcal{O}}\sum_{t\in\mathcal{T}} q^{T\rightarrow D}_{tncbomy}\right)\right] \geq 0 \perp \pi^{T\rightarrow D}_{ncmy} \geq 0 \qquad \forall n \in \mathcal{N}, c \in \mathcal{C}, b \in \mathcal{DSB}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\sum_{c'\in\mathcal{C}|(c,c')\in\mathcal{VT}} fi^{V}_{cc'}\, q^{V}_{v(n)tcc'omy} - q^{T\rightarrow V}_{tncomy}\right] \geq 0 \perp \pi^{T\rightarrow V}_{tncomy} \geq 0 \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\sum_{c\in\mathcal{C}|(cc')\in\mathcal{VT}} q^{V}_{v(n)tcc'omy} - q^{T\leftarrow V}_{tncomy}\right] \geq 0 \perp \pi^{V\rightarrow T}_{tncomy} \geq 0 \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}, c' \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[q^{A}_{acmy} - \sum_{o\in\mathcal{O}}\sum_{t\in\mathcal{T}} q^{T}_{tacomy}\right] \geq 0 \perp \pi^{A}_{acmy} \geq 0 \qquad \forall (a,c) \in \mathcal{AC}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[q^{S_{in}}_{s(n)tcomy} - q^{T\rightarrow S}_{tncomy}\right] \geq 0 \perp \pi^{T\rightarrow S}_{tncomy} \geq 0 \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[q^{S_{out}}_{s(n)tcomy} - q^{T\leftarrow S}_{tncomy}\right] \geq 0 \perp \pi^{S\rightarrow T}_{tncomy} \geq 0 \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

Mixed Complementarity Problem

$$\left(r_y d_m \left(c^{I_l}_{pibmy} + c^{I_q}_{pibmy} q^I_{pibmy}\right) - \phi^P_{pimy} + \Lambda^I_{piby}\right) \geq 0 \perp q^I_{pibmy} \geq 0 \quad \forall p \in \mathcal{P}, i \in \mathcal{I}, b \in \mathcal{IOB}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left(r_y d_m \left(-\pi^P_{n(p)comy} + c^P_{pcoy}\right) + \sum_{i \in \mathcal{I}} fi^P_{cio} \phi^P_{pisy} + \lambda^P_{pcomy}\right) \geq 0 \perp q^{P \to T}_{pcomy} \geq 0 \quad \forall p \in \mathcal{P}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\frac{r_y}{\|\Delta\|_y} c^{\Delta^I}_{piby} - \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^I_i)} \sum_{m \in \mathcal{M}} av^I_{pibm} \lambda^I_{pibmy'} + \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^I_i)} \omega^I_{piby'}\right] \geq 0 \perp \Delta^I_{piby} \geq 0 \quad \forall p \in \mathcal{P}, i \in \mathcal{I}, b \in \mathcal{IOB}, y \in \mathcal{Y}$$

$$\left(\frac{r_y}{\|\Delta\|_y} c^{\Delta P}_{pcoy} - \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^P_{co})} \sum_{m \in \mathcal{M}} \lambda^P_{pcomy'} + \omega^P_{pcoy}\right) \geq 0 \perp \Delta^P_{pcoy} \geq 0 \quad \forall p \in \mathcal{P}, c \in \mathcal{C}, o \in \mathcal{O}, y \in \mathcal{Y}$$

$$\left(\sum_{b \in \mathcal{IOB}} q^I_{pibmy} - \sum_{o \in \mathcal{O}} \sum_{c \in \mathcal{C}} fi^P_{cio} q^{P \to T}_{pcomy}\right) \geq 0 \perp \phi^P_{pimy} \geq 0 \quad \forall p \in \mathcal{P}, i \in \mathcal{I}, m \in \mathcal{S}, y \in \mathcal{Y}$$

$$\left[av^I_{pibm} \left(\sum_{y' \in \mathcal{Y} | (y - L^I_i \leq y' < y)} \Delta^I_{piby} + \Lambda^I_{piby}\right) - q^I_{pibmy}\right] \geq 0 \perp \Lambda^I_{piby} \geq 0 \quad \forall p \in \mathcal{P}, i \in \mathcal{I}, b \in \mathcal{IOB}, m \in \mathcal{S}, y \in \mathcal{Y}$$

$$\left[\left(\sum_{y' \in \mathcal{Y} | (y - L^P_{co} \leq y' < y)} \Delta^P_{pcoy} + \Lambda^P_{pcoy}\right) - q^{P \to T}_{pcomy}\right] \geq 0 \perp \lambda^P_{pcomy} \geq 0 \quad \forall p \in \mathcal{P}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left(\Omega^P_{pcoy} - \Delta^P_{pcoy}\right) \geq 0 \perp \omega^P_{pcoy} \geq 0 \quad \forall p \in \mathcal{P}, c \in \mathcal{C}, o \in \mathcal{O}, y \in \mathcal{Y}$$

$$\left(\Omega^I_{piby} - \sum_{y' \in \mathcal{Y} | (y - L^I_i \leq y' < y)} \Delta^I_{piby'}\right) \geq 0 \perp \omega^I_{piby} \geq 0 \quad \forall p \in \mathcal{P}, i \in \mathcal{I}, b \in \mathcal{IOB}, y \in \mathcal{Y}$$

$$\left[q^{P \to T}_{p(n)comy} - q^{T \leftarrow P}_{t(n)ncomy}\right] \geq 0 \perp \pi^P_{ncomy} \geq 0 \quad \forall n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\pi^{T \to D}_{ncbmy} - \tilde{P}^{T \to D}_{ncbmy}\left(\sum_{o \in \mathcal{O}} \sum_{t \in \mathcal{T}} q^{T \to D}_{tncbomy}\right)\right] \geq 0 \perp \pi^{T \to D}_{ncmy} \geq 0 \quad \forall n \in \mathcal{N}, c \in \mathcal{C}, b \in \mathcal{DSB}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\sum_{c' \in \mathcal{C} | (c, c') \in \mathcal{VT}} fi^V_{cc'} q^V_{v(n)tcc'omy} - q^{T \to V}_{tncomy}\right] \geq 0 \perp \pi^{T \to V}_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\sum_{c \in \mathcal{C} | (cc') \in \mathcal{VT}} q^V_{v(n)tcc'omy} - q^{T \leftarrow V}_{tncomy}\right] \geq 0 \perp \pi^{V \to T}_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c' \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[q^A_{acmy} - \sum_{o \in \mathcal{O}} \sum_{t \in \mathcal{T}} q^T_{tacomy}\right] \geq 0 \perp \pi^A_{acmy} \geq 0 \quad \forall (a, c) \in \mathcal{AC}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[q^{S_{in}}_{s(n)tcomy} - q^{T \to S}_{tncomy}\right] \geq 0 \perp \pi^{T \to S}_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[q^{S_{out}}_{s(n)tcomy} - q^{T \leftarrow S}_{tncomy}\right] \geq 0 \perp \pi^{S \to T}_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[r_y d_m \left(-\mathbb{1}^{NC}_{tnc} \cdot \frac{\partial \tilde{P}^{T \to D}_{ncbmy}\left(Q^{T \to D}_{ncbmy}\right)}{\partial q^{T \to D}_{tncbomy}} \cdot q^{T \to D}_{tncbomy} - \mathbb{1}^{NC}_{tnc} \cdot \tilde{P}^{T \to D}_{ncbmy}\left(Q^{T \to D}_{ncbmy}\right) - \left(1 - \mathbb{1}^{NC}_{tnc}\right) \cdot \pi^{T \to D}_{ncbmy}\right) + \phi^T_{tncomy} + d_m \lambda^T_{tncoy}\right] \geq 0 \perp q^{T \to D}_{tncbomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, b \in \mathcal{DSB}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[r_y d_m \left(\pi^P_{ncomy}\right) - \phi^T_{tncomy}\right] \geq 0 \perp q^{T \leftarrow P}_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}_p(t), c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\phi^T_{tncomy} - r_y d_m \left(\pi^{T \to V}_{tncomy}\right)\right] \geq 0 \perp q^{T \to V}_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y},$$

$$\left[r_y d_m \left(\pi^{V \to T}_{tncomy}\right) - \phi^T_{tncomy}\right] \geq 0 \perp q^{T \leftarrow V}_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\phi^T_{tncomy} - r_y d_m \left(\pi^{T \to S}_{tncomy}\right)\right] \geq 0 \perp q^{T \to S}_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[r_y d_m \left(\pi^{S \to T}_{tncomy}\right) - \phi^T_{tncomy}\right] \geq 0 \perp q^{T \leftarrow S}_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[r_y d_m \pi^A_{acmy} + \sum_{n \in \mathcal{N} | a \in \mathcal{A}_s(n)} (1 + l^A_{ac}) \phi^T_{tncomy} - \sum_{n \in \mathcal{N} | a \in \mathcal{A}_e(n)} \phi^T_{tncomy}\right] \geq 0 \perp q^T_{tacomy} \geq 0 \quad \forall t \in \mathcal{T}, o \in \mathcal{O}, (a, c) \in \mathcal{AC}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\sum_{a \in \mathcal{A}_e(n) | (a,c) \in \mathcal{AC}} q^T_{tacomy} + \sum_{n \in \mathcal{N}_p(t)} q^{T \leftarrow P}_{tncomy} + q^{T \leftarrow V}_{tncomy} + q^{T \leftarrow S}_{tncomy} - \sum_{a \in \mathcal{A}_s(n) | (a,c) \in \mathcal{AC}} (1 + l^A_{ac}) q^T_{tacomy} - \sum_{b \in \mathcal{DSB}} q^{T \to D}_{tncbomy} - q^{T \to V}_{tncomy} - q^{T \to S}_{tncomy}\right] \geq 0 \perp \phi^T_{tncomy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\Lambda^T_{tncoy} - \sum_{m \in \mathcal{M}} d_m \sum_{b \in \mathcal{DSB}} q^{T \to D}_{tncbomy}\right] \geq 0 \perp \lambda^T_{tncoy} \geq 0 \quad \forall t \in \mathcal{T}, n \in \mathcal{N}, c \in \mathcal{C}, o \in \mathcal{O}, y \in \mathcal{Y}$$

$$\left[r_y d_m \left(-\pi^{V \to T}_{tnc'omy} + fi^V_{cc'} \pi^{T \to V}_{tncomy} + c^V_{vcc'y}\right) + \lambda^V_{vcc'my}\right] \geq 0 \perp q^V_{vtcc'omy} \geq 0 \quad \forall v \in \mathcal{V}, t \in \mathcal{T}, (c, c') \in \mathcal{VT}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left(\frac{r_y}{\|\Delta\|_y} c^{\Delta V}_{vcc'y} - \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^V_{cc'})} \sum_{m \in \mathcal{M}} \lambda^V_{vcc'my'}\right) \geq 0 \perp \Delta^V_{vcc'y} \geq 0 \quad \forall v \in \mathcal{V}, (c, c') \in \mathcal{VT}, y \in \mathcal{Y}$$

$$\left(\frac{r_y}{\|\Delta\|_y} c^{\Delta^{RV}}_{vrr'cc'y} - \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^V_{cc'})} \sum_{m \in \mathcal{M}} f^{RV}_{rr'cc'} \lambda^V_{vcc'my'} + \sum_{y' \in \mathcal{Y} | (y' > y)} \sum_{m \in \mathcal{M}} \lambda^V_{vrr'my'}\right) \geq 0 \perp \Delta^{RV}_{vrr'cc'y} \geq 0 \quad \forall v \in \mathcal{V}, (c, c') \in \mathcal{VT}, y \in \mathcal{Y}$$

$$\left(\Lambda^V_{vcc'y} + \sum_{y' \in \mathcal{Y} | y - L^V_{cc'} \leq y' < y} \Delta^V_{vcc'y} + \sum_{(r,r') | ((r,r'),(cc')) \in \mathcal{RV}} \sum_{y' \in \mathcal{Y} | y - L^V_{cc'} \leq y' < y} f^{RV}_{rr'cc'} \Delta^{RV}_{vrr'cc'y} - \sum_{(r,r') | ((cc'),(r,r')) \in \mathcal{RV}} \sum_{y' \in \mathcal{Y} | y' < y} \Delta^{RV}_{vcc'rr'y} - \sum_{o \in \mathcal{O}} \sum_{t \in \mathcal{T}} q^V_{vtcc'omy}\right) \geq 0 \perp \lambda^V_{vcc'my} \geq 0 \quad \forall v \in \mathcal{V}, (c, c') \in \mathcal{VT}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[r_y d_m \left(-\pi^A_{acmy} + c^A_{acy}\right) + \lambda^A_{acmy}\right] \geq 0 \perp q^A_{acmy} \geq 0 \quad \forall (a, c) \in \mathcal{AC}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\frac{r_y}{\|\Delta\|_y} \frac{1}{2} c^{\Delta A}_{acy} - \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^A_c)} \sum_{m \in \mathcal{M}} \lambda^A_{acmy'} + \delta^A_{acy} - \delta^A_{a^{-1}(a)cy}\right] \geq 0 \perp \Delta^A_{acy} \geq 0 \quad \forall (a, c) \in \mathcal{AC}, y \in \mathcal{Y}$$

$$\left[\frac{r_y}{\|\Delta\|_y} \frac{1}{2} c^{\Delta^{RA}}_{arcy} - \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^A_c)} \sum_{m \in \mathcal{M}} f^{RA}_{rc} \lambda^A_{acmy'} + \sum_{y' \in \mathcal{Y} | y' > y} \sum_{m \in \mathcal{M}} \lambda^A_{army'} \; \delta^{RA}_{arcy} - \delta^{RA}_{a^{-1}(a)rcy}\right] \geq 0 \perp \Delta^{RA}_{arcy} \geq 0 \quad \forall a \in \mathcal{A}, (r, c) \in \mathcal{RA}, (a, r) \in \mathcal{AC}, y \in \mathcal{Y}$$

$$\left[\Lambda^A_{acy} + \sum_{y' \in \mathcal{Y} | y - L^A_c \leq y' < y} \Delta^A_{acy} + \sum_{r | (r,c) \in \mathcal{RA}} \sum_{y' \in \mathcal{Y} | y - L^A_c \leq y' < y} f^{RA}_{rc} \Delta^{RA}_{arcy} - \sum_{r | (c,r) \in \mathcal{RA}} \sum_{y' \in \mathcal{Y} | y' < y} \Delta^{RA}_{acry} - q^A_{acmy}\right] \geq 0 \perp \lambda^A_{acmy} \geq 0 \quad \forall (a, c) \in \mathcal{AC}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\Delta^A_{acy} - \Delta^A_{a^{-1}(a)cy}\right] = 0 \perp \delta^A_{acy} \quad \forall (a, c) \in \mathcal{AC}, y \in \mathcal{Y}$$

$$\left[\Delta^{RA}_{arcy} - \Delta^{RA}_{a^{-1}(a)rcy}\right] = 0 \perp \delta^{RA}_{arcy} \quad \forall a \in \mathcal{A}, (r, c) \in \mathcal{RA}, (a, r) \in \mathcal{AC}, y \in \mathcal{Y}$$

$$\left[\lambda^S_{scmy} - \left(1 - l^S_{cmm^+(m)}\right) \phi^S_{stcomy} + \phi^S_{stcom^-(m)y}\right] \geq 0 \perp q^S_{stcomy} \geq 0 \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[r_y d_m \left(\pi^{T \to S}_{tn(s)comy} + c^{S_{in}}_{scy}\right) - \left(1 - l^S_{cmm^+(m)}\right) d_m \phi^S_{stcomy}\right] \geq 0 \perp q^{S_{in}}_{stcomy} \geq 0 \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[-r_y d_m \left(\pi^{S \to T}_{tn(s)comy} - c^{S_{out}}_{scy}\right) + \left(1 - l^S_{cmm^+(m)}\right) d_m \phi^S_{stcomy}\right] \geq 0 \perp q^{S_{out}}_{stcomy} \geq 0 \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\frac{r_y}{\|\Delta\|_y} c^{\Delta S}_{scy} - \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^S_c)} \sum_{m \in \mathcal{M}} \lambda^S_{scmy'} + \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^S_c)} \omega^S_{scy'}\right] \geq 0 \perp \Delta^S_{scy} \geq 0 \quad \forall s \in \mathcal{S}, c \in \mathcal{C}, y \in \mathcal{Y}$$

$$\left[\frac{r_y}{\|\Delta\|_y} c^{\Delta^{RS}}_{srcy} - \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^S_c)} \sum_{m \in \mathcal{M}} f^{RS}_{rc} \lambda^S_{scmy'} + \sum_{y' \in \mathcal{Y} | y' > y} \sum_{m \in \mathcal{M}} \lambda^S_{srmy'} + \sum_{y' \in \mathcal{Y} | (y < y' \leq y + L^S_c)} f^{RS}_{rc} \omega^S_{scy'} - \sum_{y' \in \mathcal{Y} | y' > y} \omega^S_{sry'}\right] \geq 0 \perp \Delta^{RS}_{srcy} \geq 0 \quad \forall s \in \mathcal{S}, (r, c) \in \mathcal{RS}, y \in \mathcal{Y}$$

$$\left[\Lambda^S_{scy} + \sum_{y' \in \mathcal{Y} | y - L^S_c \leq y' < y} \Delta^S_{scy} + \sum_{r | (r,c) \in \mathcal{RS}} \sum_{y' \in \mathcal{Y} | y - L^S_c \leq y' < y} f^{RS}_{rc} \Delta^{RS}_{srcy} - \sum_{r | (c,r) \in \mathcal{RS}} \sum_{y' \in \mathcal{Y} | y' < y} \Delta^{RS}_{scry} - \sum_{o \in \mathcal{O}} \sum_{t \in \mathcal{T}} q^S_{stcomy}\right] \geq 0 \perp \lambda^S_{scmy} \geq 0 \quad \forall s \in \mathcal{S}, c \in \mathcal{C}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\left(1 - l^S_{cmm^+(m)}\right) \cdot \left(q^S_{stcomy} + d_m \left(q^{S_{in}}_{stcomy} - q^{S_{out}}_{stcomy}\right)\right) - q^S_{stcom^+(m)y}\right] \geq 0 \perp \phi^S_{stcomy} \geq 0 \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, c \in \mathcal{C}, o \in \mathcal{O}, m \in \mathcal{M}, y \in \mathcal{Y}$$

$$\left[\Omega^S_{scy} - \sum_{y' \in \mathcal{Y} | y - L^S_c \leq y' < y} \Delta^S_{scy} - \sum_{r | (r,c) \in \mathcal{RS}} \sum_{y' \in \mathcal{Y} | y - L^S_c \leq y' < y} f^{RS}_{rc} \Delta^{RS}_{srcy} + \sum_{r | (c,r) \in \mathcal{RS}} \sum_{y' \in \mathcal{Y} | y' < y} \Delta^{RS}_{scry}\right] \geq 0 \perp \omega^S_{scy} \geq 0 \quad \forall s \in \mathcal{S}, c \in \mathcal{C}, y \in \mathcal{Y}$$

Reformulation: MCP $\longrightarrow$ Convex Optimization Problem

$$
\max_{\substack{q^I_{pibmy},\, q^{P\to T}_{pcomy},\, \Delta^I_{piby},\, \Delta^P_{pcoy},\, q^{T\to D}_{tncbomy},\, q^V_{vtcdomy},\, \Delta^V_{vcc'y},\\ \Delta^{RV}_{vrr'cc'y},\, q^T_{tacomy},\, \Delta^A_{acy},\, \Delta^{RA}_{arcy},\, q^S_{stcomy},\, q^{S_{in}}_{stcomy},\, q^{S_{out}}_{stcomy},\, \Delta^S_{scy},\, \Delta^{RS}_{scry}}} \sum_{y\in\mathcal{Y}} r_y
\left[
\begin{aligned}
&\sum_{m\in\mathcal{M}} d_m \sum_{c\in\mathcal{C}}\sum_{n\in\mathcal{N}} \left(
\begin{aligned}
&\frac{1}{2}\sum_{b\in\mathcal{DSB}} \beta^D_{ncbmy}\left(\sum_{t\in\mathcal{T}}\sum_{o\in\mathcal{O}} q^{T\to D}_{tncbomy}\right)^2 \\
&+ \sum_{b\in\mathcal{DSB}} \alpha^D_{ncbmy}\left(\sum_{t\in\mathcal{T}}\sum_{o\in\mathcal{O}} q^{T\to D}_{tncbomy}\right) \\
&+\frac{1}{2}\sum_{t\in\mathcal{T}} \mathbb{1}^{NC}_{tnc} \sum_{b\in\mathcal{DSB}} \beta^D_{ncbmy}\left(\sum_{o\in\mathcal{O}} q^{T\to D}_{tncbomy}\right)^2
\end{aligned}\right) \\
&-\sum_{p\in\mathcal{P}}\sum_{i\in\mathcal{I}}\sum_{m\in\mathcal{M}} d_m \sum_{b\in\mathcal{IOB}}\left(c^{I_l}_{pibmy} q^I_{pibmy} + \frac{1}{2} c^{I_q}_{pibmy}\left(q^I_{pibmy}\right)^2\right) \\
&-\sum_{p\in\mathcal{P}}\sum_{i\in\mathcal{I}}\sum_{b\in\mathcal{IOB}} \frac{1}{\|\Delta\|_y} c^{\Delta^I}_{piby}\Delta^I_{piby} \\
&-\sum_{p\in\mathcal{P}}\sum_{c\in\mathcal{C}}\sum_{o\in\mathcal{O}}\sum_{m\in\mathcal{M}} d_m c^P_{pcoy} q^{P\to T}_{pcomy} \\
&-\sum_{p\in\mathcal{P}}\sum_{c\in\mathcal{C}}\sum_{o\in\mathcal{O}} \frac{1}{\|\Delta\|_y} c^{\Delta P}_{pcoy}\Delta^P_{pcoy} \\
&-\sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}}\sum_{(c,c')\in\mathcal{VT}}\sum_{o\in\mathcal{O}}\sum_{m\in\mathcal{M}} d_m c^V_{vcc'y} q^V_{vtcc'omy} \\
&-\sum_{v\in\mathcal{V}}\sum_{(c,c')\in\mathcal{VT}} \frac{1}{\|\Delta\|_y} c^{\Delta V}_{vcc'y}\Delta^V_{vcc'y} \\
&-\sum_{v\in\mathcal{V}}\sum_{((r,r'),(c,c'))\in\mathcal{RV}} \frac{1}{\|\Delta\|_y} c^{\Delta^{RV}}_{vrr'cc'y}\Delta^{RV}_{vrr'cc'y} \\
&-\sum_{t\in\mathcal{T}}\sum_{(a,c)\in\mathcal{AC}}\sum_{o\in\mathcal{O}}\sum_{m\in\mathcal{M}} d_m c^A_{acy} q^T_{tacomy} \\
&-\sum_{(a,c)\in\mathcal{AC}} \frac{1}{\|\Delta\|_y}\frac{1}{2} c^{\Delta A}_{acy}\Delta^A_{acy} \\
&-\sum_{a\in\mathcal{A}}\sum_{(r,c)\in\mathcal{RA}|(a,r)\in\mathcal{AC}} \frac{1}{\|\Delta\|_y}\frac{1}{2} c^{\Delta^{RA}}_{arcy}\Delta^{RA}_{arcy} \\
&-\sum_{s\in\mathcal{S}}\sum_{t\in\mathcal{T}}\sum_{c\in\mathcal{C}}\sum_{o\in\mathcal{O}}\sum_{m\in\mathcal{M}} d_m c^{S_{in}}_{scy} q^{S_{in}}_{stcomy} \\
&-\sum_{s\in\mathcal{S}}\sum_{t\in\mathcal{T}}\sum_{c\in\mathcal{C}}\sum_{o\in\mathcal{O}}\sum_{m\in\mathcal{M}} d_m c^{S_{out}}_{scy} q^{S_{out}}_{stcomy} \\
&-\sum_{s\in\mathcal{S}}\sum_{c\in\mathcal{C}} \frac{1}{\|\Delta\|_y} c^{\Delta S}_{scy}\Delta^S_{scy} \\
&-\sum_{s\in\mathcal{S}}\sum_{(r,c)\in\mathcal{RS}} \frac{1}{\|\Delta\|_y} c^{\Delta^{RS}}_{srcy}\Delta^{RS}_{srcy}
\end{aligned}
\right]
$$

$$
\text{s.t.} \sum_{o\in\mathcal{O}}\sum_{c\in\mathcal{C}} fi^P_{cio} q^{P\to T}_{pcomy} \le \sum_{b\in\mathcal{IOB}} q^I_{pibmy} \qquad \forall p\in\mathcal{P}, i\in\mathcal{I}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\phi^P_{pimy})
$$

$$
q^I_{pibmy} \le av^I_{pibm}\left(\Lambda^I_{piby} + \sum_{y'\in\mathcal{Y}|(y-L^I_i\le y'<y)} \Delta^I_{piby}\right) \qquad \forall p\in\mathcal{P}, i\in\mathcal{I}, b\in\mathcal{IOB}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\Lambda^I_{piby})
$$

$$
q^{P\to T}_{pcomy} \le \left(\Lambda^P_{pcoy} + \sum_{y'\in\mathcal{Y}|(y-L^P_{co}\le y'<y)} \Delta^P_{pcoy}\right) \qquad \forall p\in\mathcal{P}, c\in\mathcal{C}, o\in\mathcal{O}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\lambda^P_{pcomy})
$$

$$
\Delta^P_{pcoy} \le \Omega^P_{pcoy} \qquad \forall p\in\mathcal{P}, c\in\mathcal{C}, o\in\mathcal{O}, y\in\mathcal{Y} \quad (\omega^P_{pcoy})
$$

$$
\sum_{y'\in\mathcal{Y}|(y-L^I_i\le y'<y)} \Delta^I_{piby'} \le \Omega^I_{piby} \qquad \forall p\in\mathcal{P}, i\in\mathcal{I}, b\in\mathcal{IOB}, y\in\mathcal{Y} \quad (\omega^I_{piby})
$$

$$
\begin{aligned}
&\left(\sum_{a\in\mathcal{A}_s(n)|(a,c)\in\mathcal{AC}} (1+l^A_{ac}) q^T_{tacomy} + \sum_{b\in\mathcal{DSB}} q^{T\to D}_{tncbomy} + \sum_{c'\in\mathcal{C}|(c,c')\in\mathcal{VT}} fi^V_{cc'} q^V_{v(n)tcc'omy} + q^{S_{in}}_{s(n)tcomy}\right) \\
&\le \left(\sum_{a\in\mathcal{A}_e(n)|(a,c)\in\mathcal{AC}} q^T_{tacomy} + \sum_{c'\in\mathcal{C}|(c',c)\in\mathcal{VT}} q^V_{v(n)tc'comy} + \sum_{p\in\mathcal{P}(t,n)} q^{P\to T}_{pcomy} + q^{S_{out}}_{s(n)tcomy}\right)
\end{aligned}
\qquad \forall t\in\mathcal{T}, n\in\mathcal{N}, c\in\mathcal{C}, o\in\mathcal{O}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\phi^T_{tncomy})
$$

$$
\sum_{m\in\mathcal{M}} d_m \sum_{b\in\mathcal{DSB}} q^{T\to D}_{tncbomy} \le \Lambda^T_{tncoy} \qquad \forall t\in\mathcal{T}, n\in\mathcal{N}, c\in\mathcal{C}, o\in\mathcal{O}, y\in\mathcal{Y} \quad (\lambda^T_{tncoy})
$$

$$
\begin{aligned}
&\sum_{o\in\mathcal{O}}\sum_{t\in\mathcal{T}} q^V_{vtcc'omy} \\
&\le \left(\Lambda^V_{vcc'y} + \sum_{y'\in\mathcal{Y}|y-L^V_{cc'}\le y'<y} \Delta^V_{vcc'y} + \sum_{(r,r')|((r,r'),(cc'))\in\mathcal{RV}}\ \sum_{y'\in\mathcal{Y}|y-L^V_{cc'}\le y'<y} f^{RV}_{rr'cc'}\Delta^{RV}_{vrr'cc'y} - \sum_{(r,r')|((cc'),(r,r'))\in\mathcal{RV}}\ \sum_{y'\in\mathcal{Y}|y'<y} \Delta^{RV}_{vcc'rr'y}\right)
\end{aligned}
\qquad \forall v\in\mathcal{V}, (c,c')\in\mathcal{VT}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\lambda^V_{vcdsy})
$$

$$
\sum_{o\in\mathcal{O}}\sum_{t\in\mathcal{T}} q^T_{tacomy} \le \left(\Lambda^A_{acy} + \sum_{y'\in\mathcal{Y}|y-L^A_c\le y'<y} \Delta^A_{acy} + \sum_{r|(r,c)\in\mathcal{RA}}\ \sum_{y'\in\mathcal{Y}|y-L^A_c\le y'<y} f^{RA}_{rc}\Delta^{RA}_{arcy} - \sum_{r|(c,r)\in\mathcal{RA}}\ \sum_{y'\in\mathcal{Y}|y'<y} \Delta^{RA}_{acry}\right) \qquad \forall (a,c)\in\mathcal{AC}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\lambda^A_{acmy})
$$

$$
\Delta^A_{acy} = \Delta^A_{a^{-1}(a)cy} \qquad \forall (a,c)\in\mathcal{AC}, y\in\mathcal{Y} \quad (\delta^A_{acy})
$$

$$
\Delta^{RA}_{arcy} = \Delta^{RA}_{a^{-1}(a)rcy} \qquad \forall a\in\mathcal{A}, (r,c)\in\mathcal{RA}, (a,r)\in\mathcal{AC}, y\in\mathcal{Y} \quad (\delta^{RA}_{arcy})
$$

$$
\begin{aligned}
&\sum_{o\in\mathcal{O}}\sum_{t\in\mathcal{T}} q^S_{stcomy} \\
&\le \left(\Lambda^S_{scy} + \sum_{y'\in\mathcal{Y}|y-L^S_c\le y'<y} \Delta^S_{scy} + \sum_{r|(r,c)\in\mathcal{RS}}\ \sum_{y'\in\mathcal{Y}|y-L^S_c\le y'<y} f^{RS}_{rc}\Delta^{RS}_{srcy} - \sum_{r|(c,r)\in\mathcal{RS}}\ \sum_{y'\in\mathcal{Y}|y'<y} \Delta^{RS}_{scry}\right)
\end{aligned}
\qquad \forall s\in\mathcal{S}, c\in\mathcal{C}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\lambda^S_{scmy})
$$

$$
q^S_{stcom^+(m)y} \le \left(1 - l^S_{cmm^+(m)}\right)\cdot\left[q^S_{stcomy} + d_m\left(q^{S_{in}}_{stcomy} - q^{S_{out}}_{stcomy}\right)\right] \qquad \forall s\in\mathcal{S}, t\in\mathcal{T}, c\in\mathcal{C}, o\in\mathcal{O}, m\in\mathcal{M}, y\in\mathcal{Y} \quad (\phi^S_{stcomy})
$$

$$
\left(\sum_{y'\in\mathcal{Y}|y-L^S_c\le y'<y} \Delta^S_{scy} + \sum_{r|(r,c)\in\mathcal{RS}}\ \sum_{y'\in\mathcal{Y}|y-L^S_c\le y'<y} f^{RS}_{rc}\Delta^{RS}_{srcy} - \sum_{r|(c,r)\in\mathcal{RS}}\ \sum_{y'\in\mathcal{Y}|y'<y} \Delta^{RS}_{scry}\right) \le \Omega^S_{scy} \qquad \forall s\in\mathcal{S}, c\in\mathcal{C}, y\in\mathcal{Y} \quad (\omega^S_{scy})
$$

$$
\begin{pmatrix}
q^I_{pibmy}, q^{P\to T}_{pcomy}, \Delta^I_{piby}, \Delta^P_{pcoy}, q^{T\to D}_{tncbomy}, \\
q^V_{vtcc'omy}, \Delta^V_{vcc'y}, \Delta^{RV}_{vrr'cc'y}, q^T_{tacomy}, \Delta^A_{acy}, \\
\Delta^{RA}_{arcy}, q^S_{stcomy}, q^{S_{in}}_{stcomy}, q^{S_{out}}_{stcomy}, \Delta^S_{scy}, \Delta^{RS}_{scry}
\end{pmatrix} \ge 0
$$

Agenda

Implementation and Validation

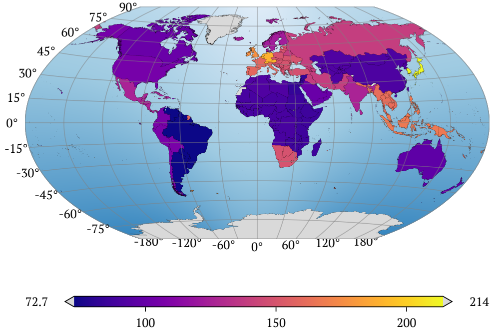
- Two model versions implemented in the form of a standalone *Julia* package
  - https://github.com/LukasBarner/HydrOGEnMod.jl,
- Documentation and replication script
  - Hosted at https://lukasbarner.github.io/HydrOGEnMod.jl/dev/
- Detailed Testing
  - Complementarity approach and convex reformulation validated
  - Detailed cases of 28 data sets
  - Functionality tests related to data and plotting utilities
  - Over 95 % of the source code are covered by tests.
  - Documentation of validation procedures provided in a 156 page technical supplement
- Accepted with Energy

Agenda

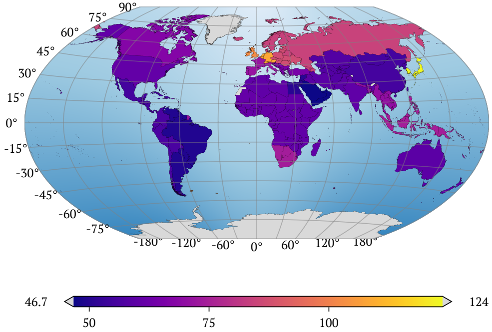
Data

- GIS analysis with the GlobalEnergyGIS package (Mattsson et al. 2021).
  - Historic weather data from ERA5
  - Hypothetical hourly capacity factors for the year 2018
  - Areas excluded, such as natural reserves, water bodies, croplands, etc.
  - Numerous assumptions (e.g. on maximum water depth for offshore wind, distances to coastlines, population densities, remoteness from grid infrastructure, renewable-build-specific parameters etc.)
  - Subtract capacities required to meed seasonal electricity demand from renewables exclusively
  - Investment cost projections for renewables roughly follow IEA (2022) and IRENA (2023)
  - Nuclear investment costs regionally adjusted, but generally follow Göke, Wimmers, and von Hirschhausen (2023) with a surcharge for decommissioning.
  - Electrolyzer investment costs in line with IRENA (2021), most conversion related cost follow IEA (2019)
  - Inverse demand functions calibrated in line with IEA (2022) Net Zero Emissions by 2050 scenario
    - 300 BCMe (2900 TW h) hydrogen and derivatives demand by 2030 and 1500 BCMe (14 750 TW h) by 2050
  - Detailed overview of data assumptions can be seen from code repository

- Significant price spreads can be observed
- Early on, locations rich in wind are most attractive, while over time solar regions tend to be most lucrative



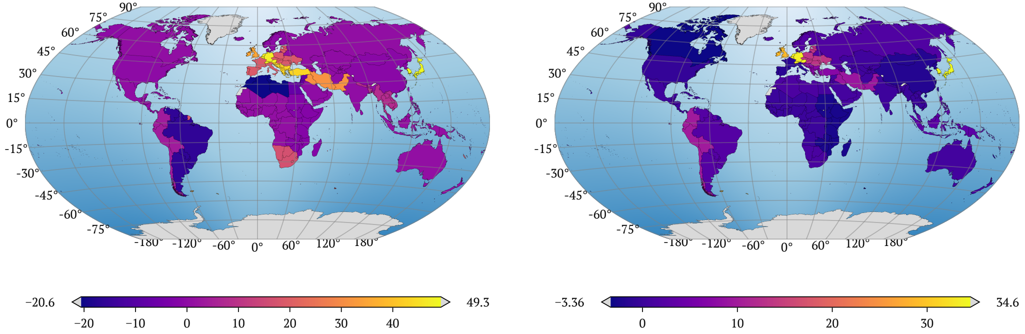
(a) Weighted Average 2030



(b) Weighted Average 2050

Figure: Prices for Hydrogen with Market Power in €/MWh

- Mostly, Europe and Japan are affected by the price increase due to strategic behavior
- For some regions, cheaper resources are domestically available as exports are strategically withheld



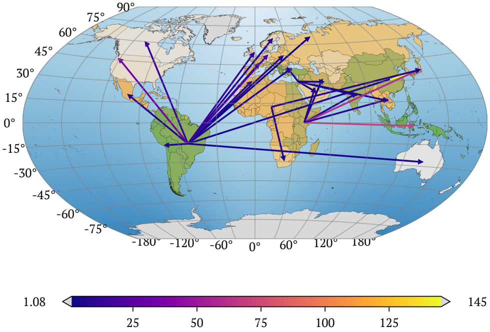
(a) Weighted Average 2030

(b) Weighted Average 2050

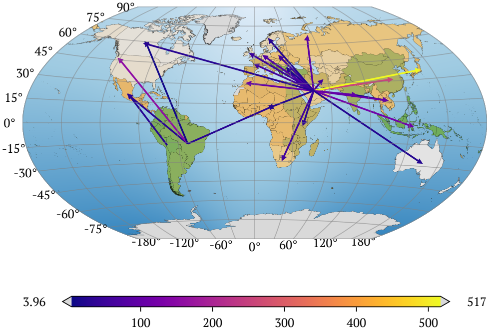
Figure: Seasonal Price Increase due to Strategic Behavior in €/MWh

Results – Trade Flows under Perfect Competition

- Under perfect competition, few large ammonia exporters emerge
- Again, locations rich in wind are most attractive early on, while over time solar regions tend to be most lucrative



(a) Competitive Flows 2030

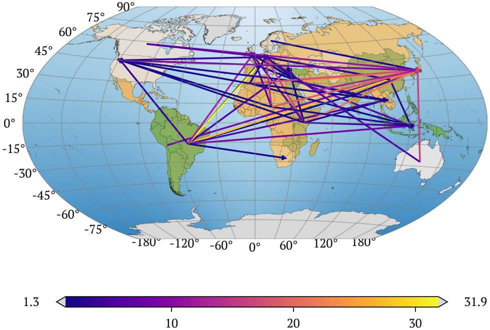


(b) Competitive Flows 2050

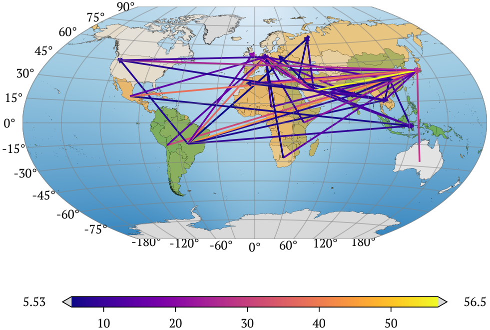
Figure: Annual Trade Flows for Ammonia in TW h

Results – Trade Flows under Market Power

- Supply patterns diverge
- Withheld quantities are partially offset by other suppliers



(a) Oligopolistic Flows 2030



(b) Oligopolistic Flows 2050

Figure: Annual Trade Flows for Ammonia in TW h

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Conclusion and Outlook

Conclusion

- Strategic behavior of exporters can have significant effects on prices
- Twofold narrative for potential exporting regions to incentivize strategic behavior:
  - Profits of exporters increase from higher foreign prices
  - Prices paid by domestic consumers decrease.
- Nuclear hydrogen not cost competitive

Outlook

- Reduced complexity case study
  - More detailed scenario analysis, Additional derivatives
  - Higher spatial and temporal resolution
  - Stochasticity and decomposition
  - Different allocation of exporters
  - Cross validation of renewable potentials (esp. Southern Africa)
  - Natural gas and CCTS

Outlook

- Next model runs:
  - Including global natural gas markets and simplified representation of electricity markets
  - Structured along the following regions:

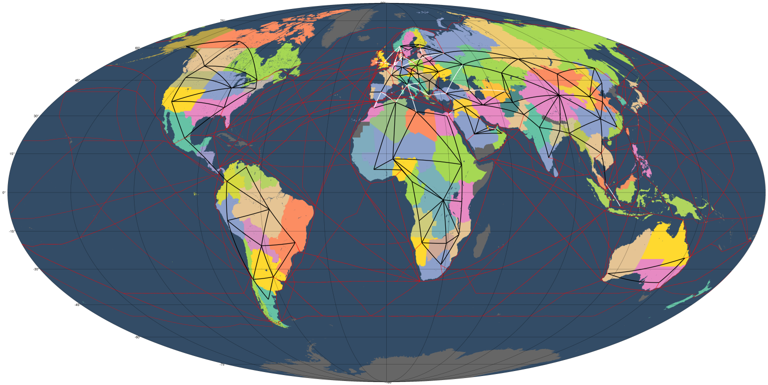

Figure: Outlook to future transportation network

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Discussion

Agenda

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Appendix: Notation

Parameter	Explanation
$\frac{1}{\Vert\Delta\Vert_y}$	Scaling of investment costs by the number of modeled years.
$\mathbb{1}^{NC}_{tnc}$	Factor indicating if trader t is able to effectively withhold quantities of commodity c in node n. If set to 1, Nash-Cournot behavior is assumed in the respective node, while a value of 0 implies perfectly competitive behavior (or equivalent regulation). If a conjectural variation approach is assumed, values in between may be taken.
av^I_{pibm}	Availability of input i in block b during time step m.
r_y	Discount factor indicating temporal preferences with respect to yearly profits. Preferences are assumed to be consistent between players.
d_m	Weighting factor in time step m. Can be used to model aggregation.
$c^{\Delta^I}_{piby}$	Cost coefficient of producer p for input expansion of i belonging to block b in year y.
$c^{I_l}_{pibmy}$	Linear operational cost coefficient of producer p for input i belonging to block b in time step m of year y.
$c^{I_q}_{pibmy}$	Quadratic cost coefficient of producer p for input i belonging to block b in time step m of year y.
c^P_{pcoy}	Production cost of producer p for commodity c of origin o in year y.
$c^{\Delta P}_{pcoy}$	Unit cost for expanding producer p's production capacity of commodity c in year y.
fi^P_{cio}	Factor intensity. Indicates how many units of input i are used to produce one unit of commodity c for origin o.
L^I_i	Lifetime of capacity investments into input procurement.
L^P_{co}	Lifetime of technology used to produce commodity c from origin o.
Λ^P_{pcoy}	Exogenous capacity of producer p to produce commodity c from origin o.
Λ^I_{piby}	Exogenous capacity of producer p for input i in time step m of year y.
Λ^T_{tncoy}	Maximum quantity of commodity c from origin o sold in year y by trader t in node n.
Ω^I_{piby}	Capacity expansion restriction for input i to block b of producer p in year y.
Ω^P_{pcoy}	Capacity expansion restriction for commodity c from origin o of producer p in year y.
$fi^V_{cc'}$	Factor intensity indicating how much of commodity c is used in when converting to commodity c'.
l^A_{ac}	Loss for transporting commodity c on arc a.
$c^V_{vcc'y}$	Cost of converter v to convert commodity c to commodity c' in y.
$c^{\Delta V}_{vcc'y}$	Cost of converter v to extend conversion capacity from c to c' in y.
$c^{\Delta^{RV}}_{vrr'cc'y}$	Cost of repurposing conversion capacity (r, r') to (c, c').
$f^{RV}_{rr'cc'}$	Factor indicating how much conversion capacity for cc' is created when one unit of conversion capacity rr' is repurposed.
$\Lambda^V_{vcc'y}$	Exogenous conversion capacity of converter v from c to c' in year y.
$L^V_{cc'}$	Lifetime of endogenously added conversion capacity from c to c'.
c^A_{acy}	Unit cost for transporting commodity c along arc a in year y.
$c^{\Delta A}_{acy}$	Cost for expanding transport capacity of commodity c along arc a in year y.
$c^{\Delta^{RA}}_{arcy}$	Cost for repurposing transport capacity of commodity r to c.
f^{RA}_{rc}	Factor indicating how much transport capacity of c is created when one unit of capacity for r is repurposed.
Λ^A_{acy}	Exogenous transport capacity of commodity c on arc a.
L^A_c	Lifetime of endogenously added transport capacity of commodity c.
$l^S_{scmm^+(m)}$	Storage losses of storage system operator s when storing commodity c from time step m to $m^+(m)$ during year y.
$c^{S_{in}}_{scy}$	Storage costs of storage system operator s when injecting commodity c in year y.
$c^{S_{out}}_{scy}$	Storage costs of storage system operator s when extracting commodity c in year y.
$c^{\Delta S}_{scy}$	Storage capacity expansion costs of storage system operator s for commodity c in year y.
$c^{\Delta^{RS}}_{srcy}$	Cost of repurposing storage capacity from r to c.
f^{RS}_{rc}	Factor indicating how much storage capacity of c is created when one unit of capacity for r is repurposed.
Λ^S_{scy}	Exogenous storage capacity of storage system operator s for commodity c in year y.
Ω^S_{scy}	Storage capacity expansion restriction of storage system operator s for commodity c in year y.
L^S_c	Technology lifetime for storage of commodity c.

Set	Explanation
$\mathcal{A}$	Set of all arcs.
$\mathcal{AC}$	Set of all arcs (a, c) on which commodity c can be transported.
$\mathcal{C}$	Set of all hydrogen related commodities.
$\mathcal{DSB}$	Set of demand blocks of one commodity.
$\mathcal{I}$	Set of all inputs.
$\mathcal{IOB}$	Set of input cost blocks.
$\mathcal{M}$	Set of all time steps within one year.
$\mathcal{N}$	Set of all nodes.
$\mathcal{O}$	Set of all production origins.
$\mathcal{P}$	Set of all producers.
$\mathcal{PT}$	Set of all possible production technologies (c, o) of commodities c from origin o.
$\mathcal{RA}$	Set of all possible repurposings of arcs between commodities (c, c') .
$\mathcal{RS}$	Set of all possible repurposings of storages between commodities (c, c') .
$\mathcal{RV}$	Set of all possible repurposings of conversion technologies between commodities $((r, r'), (cc'))$.
$\mathcal{S}$	Set of all storage system operators.
$\mathcal{T}$	Set of all traders.
$\mathcal{V}$	Set of all converters.
$\mathcal{VT}$	Set of all possible conversions (c, c') between commodities.
$\mathcal{Y}$	Set of all years.

Mapping	Explanation
$\mathcal{A}_e(n)$	All transportation arcs a that end in node n. Defined for all $n \in \mathcal{N}$.
$\mathcal{A}_s(n)$	All transportation arcs a that start in node n. Defined for all $n \in \mathcal{N}$.
$a^{-1}(a)$	Arc going in the opposite direction of a. Defined for all $a \in \mathcal{A}$.
$n(p)$	Mapping each producer p to the corresponding node n. Defined for all $p \in \mathcal{P}$.
$\mathcal{P}(t, n)$	Set containing all domestic producers of trader t in node n. Defined for all $t \in \mathcal{T}$, $n \in \mathcal{N}$.
$\mathcal{N}_P(t)$	Set of all production nodes of trader t. Defined for all $t \in \mathcal{T}$.
$n(s)$	Mapping each storage system operator s to the corresponding node n. Defined for all $s \in \mathcal{S}$.
$s(n)$	Domestic storage system operator of node n. Defined for all $n \in \mathcal{N}$.
$v(n)$	Domestic converter of node n. Defined for all $n \in \mathcal{N}$.
$m^+(m)$	Time step following m. The step following the last one is the first, i.e. $m^+(m[end]) = m[1]$. Defined for all $m \in \mathcal{M}$.
$m^-(m)$	Time step preceding m. The step preceding the first one is the last, i.e. $m^-(m[1]) = m[end]$. Defined for all $m \in \mathcal{M}$.

Variable	Explanation
$q^{P\rightarrow T}_{pcomy}$	Quantity of commodity c from origin o sold from producer p to trader in time step m of year y.
Δ^I_{piby}	Expansion of producer p's capacity to procure input i from block b, invested in year y.
Δ^P_{pcoy}	Expansion of producer p's yearly capacity to produce commodity c from origin o, invested in year y.
q^I_{pibmy}	Quantity of input i procured by producer p each time step m in year y, valid in block b.
$q^{T\leftarrow P}_{tncomy}$	Quantity of commodity c from origin o acquired by trader t in node n during time step m of year y.
$q^{T\rightarrow D}_{tncbomy}$	Quantity of commodity c from origin o sold by trader t to demand block b in node n during time step m of year y.
$q^{T\rightarrow V}_{tncomy}$	Quantity of commodity c from origin o sold by trader t to converter in node n during time step m of year y.
$q^{T\leftarrow V}_{tncomy}$	Quantity of commodity c from origin o sold to trader t by converter in node n during time step m of year y.
$q^{T\rightarrow S}_{tncomy}$	Quantity of commodity c sold by trader t to storage in node n during time step m of year y.
$q^{T\leftarrow S}_{tncomy}$	Quantity of commodity c sold to trader t by storage in node n during time step m of year y.
q^T_{tacomy}	Flow of commodity c belonging to trader t on arc a during time step m of year y.
$q^V_{vtcc'omy}$	Commodity c converted to c' of origin o by converter v on behalf of trader t during time step m of year y.
$\Delta^V_{vcc'y}$	Conversion capacity expansion from commodity c to c' of year y.
$\Delta^{RV}_{vrr'cc'y}$	Conversion capacity repurposing from rr' to cc' during year y.
q^A_{acmy}	Total flow of commodity c on arc a during time step m of year y.
Δ^A_{acy}	Transport capacity expansion for commodity c on arc a, invested in year y.
Δ^{RA}_{arcy}	Transport capacity repurposing from commodity r to c on arc a in year y.
q^S_{stcomy}	Total quantity of commodity c from origin o stored at the beginning of time step m by storage system operator s on behalf of trader t in year y.
$q^{S_{in}}_{stcomy}$	Quantity of commodity c from origin o injected into storage during time step m by storage system operator s on behalf of trader t in year y.
$q^{S_{out}}_{stcomy}$	Quantity of commodity c from origin o extracted from storage during time step m by storage system operator s on behalf of trader t in year y.
Δ^S_{scy}	Storage capacity expansion for commodity c by storage system operator s in year y.
Δ^{RS}_{srcy}	Storage capacity repurposing from commodity r to c by storage system operator s in year y.
$Q^{T\rightarrow D}_{ncbmy}$	Aggregate supply of commodity c to block b in node n.

Variable	Explanation
π^P_{ncomy}	Price for commodity c of origin o in time step s of year y in node n.
$\pi^{T\rightarrow D}_{ncbmy}$	Demand block b's price for commodity c during time step m of year y in node n.
$\pi^{T\rightarrow V}_{tncomy}$	Price paid by converter for commodity c of origin o during time step m of year y in node n.
$\pi^{V\rightarrow T}_{tncomy}$	Price paid to converter for commodity c of origin o during time step m of year y in node n.
$\pi^{T\rightarrow S}_{tncomy}$	Price paid by storage system operator for commodity c from origin o during time step m of year y in node n.
$\pi^{S\rightarrow T}_{tncomy}$	Price paid to storage system operator for commodity c from origin o during time step m of year y in node n.
π^A_{acmy}	Price paid for transporting commodity c along arc a in time step m of year y.
ϕ^P_{pisy}	Dual to producer p's mass balance constraint.
ϕ^T_{tncosy}	Dual to trader t's flow mass balance constraint.
ϕ^S_{stcomy}	Dual to storage system operator s's mass balance constraint.
Λ^I_{piby}	Dual to producer p's input block constraint.
λ^P_{pcosy}	Dual to producer p's production capacity constraint.
λ^T_{tncoy}	Dual to trader t's sales restriction constraint.
ω^I_{piby}	Dual to producer p's input procurement capacity constraint.
ω^P_{pcoy}	Dual to producer p's production capacity expansion constraint.
ω^S_{scy}	Dual to storage system operator s's capacity expansion constraint.
$\lambda^V_{vcc'sy}$	Dual to converter v's converstion capacity constraint.
λ^A_{acsy}	Dual to storage system operator's capacity constraint.
λ^S_{scmy}	Dual to storage system operator's capacity constraint.
δ^A_{acy}	Dual to storage system operator's equal capacity expansion constraint.
δ^{RA}_{arcy}	Dual to storage system operator's equal capacity repurposing constraint.