Appendix to the paper: Contracts for Gas Prioritization to Power Plants and Grid Reliability during Winter Emergencies

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A Nomenclature

Bold upper case letters are used to denote sets. Parameters are represented by upper case letters, while variables and indices are denoted by smaller case letters. Greek letters denote parameters and variables of the gas system.

Indices

g	Generator
i	Node in the power system
ij	Power transmission line connecting nodes i and j
m	Gas junction
mn	Gas pipeline segment connecting junctions m and n
z	Gas pricing zone

Sets

$\mathbf{G}$	Set of generators
$\mathbf{G_g}$	Set of gas-fired generators, $\mathbf{G_g} \subseteq \mathbf{G}$
$\mathbf{G_g^{LDC}}$	Set of gas-fired generators connected to LDCs, $\mathbf{G_g^{LDC}} \subseteq \mathbf{G_g}$
$\mathbf{G_g^{LDC,Firm}}$	Set of gas-fired generators holding firm contracts and connected to LDCs, $\mathbf{G_g^{LDC,Firm}} \subseteq \mathbf{G_g^{LDC}}$
$\mathbf{G_g^{LDC,Int}}$	Set of gas-fired generators holding interruptible contracts and connected to LDCs, $\mathbf{G_g^{LDC,Int}} \subseteq \mathbf{G_g^{LDC}}$
$\mathbf{G_g^{Pipe}}$	Set of gas-fired generators connected to pipelines, $\mathbf{G_g^{Pipe}} \subseteq \mathbf{G_g}$
$\mathbf{G_g^{Pipe,Firm}}$	Set of gas-fired generators holding firm contracts and connected to pipelines, $\mathbf{G_g^{Pipe,Firm}} \subseteq \mathbf{G_g^{Pipe}}$
$\mathbf{G_g^{Pipe,Int}}$	Set of gas-fired generators holding interruptible contracts and connected to pipelines, $\mathbf{G_g^{Pipe,Int}} \subseteq \mathbf{G_g^{Pipe}}$
$\mathbf{G_{gm}^{LDC,Firm}}$	Set of gas-fired generators holding firm contracts and connected to LDCs at junction m, $\mathbf{G_{gm}^{LDC,Firm}} \subseteq \mathbf{G_g^{LDC,Firm}}$

$\mathbf{G_{gm}^{LDC,Int}}$	Set of gas-fired generators holding interruptible contracts and connected to LDCs at junction m, $\mathbf{G_{gm}^{LDC,Int}} \subseteq \mathbf{G_{g}^{LDC,Int}}$
$\mathbf{G_{gm}^{Pipe,Firm}}$	Set of gas-fired generators holding firm contracts and connected to pipelines at junction m, $\mathbf{G_{gm}^{Pipe,Firm}} \subseteq \mathbf{G_{g}^{Pipe,Firm}}$
$\mathbf{G_{gm}^{Pipe,Int}}$	Set of gas-fired generators holding interruptible contracts and connected to pipelines at junction m, $\mathbf{G_{gm}^{Pipe,Int}} \subseteq \mathbf{G_{g}^{Pipe,Int}}$
$\mathbf{G_i}$	Set of generators connected to node i, $\mathbf{G_i} \subseteq \mathbf{G}$
$\mathbf{G_{ng}}$	Set of non-gas-fired generators, $\mathbf{G_{ng}} \subseteq \mathbf{G}$
$\mathbf{I}$	Set of nodes in the power system
$\mathbf{L}$	Set of power transmission lines
$\mathbf{M}$	Set of gas junctions
$\mathbf{M_{g}^{LDC,Firm}}$	Set of gas junctions including gas-fired generators holding firm contracts and connected to LDCs, $\mathbf{M_{g}^{LDC,Firm}} \subseteq \mathbf{M}$
$\mathbf{M_{g}^{LDC,Int}}$	Set of gas junctions including gas-fired generators holding interruptible contracts and connected to LDCs, $\mathbf{M_{g}^{LDC,Int}} \subseteq \mathbf{M}$
$\mathbf{M_{g}^{Pipe,Firm}}$	Set of gas junctions including gas-fired generators holding firm contracts and connected to pipelines, $\mathbf{M_{g}^{Pipe,Firm}} \subseteq \mathbf{M}$
$\mathbf{M_{g}^{Pipe,Int}}$	Set of gas junctions including gas-fired generators holding interruptible contracts and connected to pipelines, $\mathbf{M_{g}^{Pipe,Int}} \subseteq \mathbf{M}$
$\mathbf{M_{g}^{LDC/Pipe,Firm}}$	Set of gas junctions including gas-fired generators holding firm contracts that are connected either to LDCs or pipelines, $\mathbf{M_{g}^{LDC,Firm}} \cap \mathbf{M_{g}^{Pipe,Firm}}$
$\mathbf{M_{g}^{Pipe,AEA}}$	Set of gas junctions including gas-fired generators holding firm contracts and AEAs connected to pipelines, $\mathbf{M_{g}^{Pipe,AEA}} \subseteq \mathbf{M_{g}^{Pipe,Firm}}$
$\mathbf{M_{g}^{LDC,AEA}}$	Set of gas junctions including gas-fired generators holding firm contracts and AEAs connected to LDCs, $\mathbf{M_{g}^{LDC,AEA}} \subseteq \mathbf{M_{g}^{LDC,Firm}}$
$\mathbf{M_z}$	Set of gas junctions in gas pricing zone z, $\mathbf{M_z} \subseteq \mathbf{M}$
$\mathbf{Q}$	Set of gas pipeline segments
$\mathbf{Q_a}$	Set of active gas pipeline segments, $\mathbf{Q_a} \subseteq \mathbf{Q}$
$\mathbf{Q_p}$	Set of passive gas pipeline segments, $\mathbf{Q_p} \subseteq \mathbf{Q}$
$\mathbf{Z}$	Set of gas pricing zones

Parameters

C_{ng}	Marginal cost of non-gas-fired generator, $g \in \mathbf{G_{ng}}$ [$/MWh]
$CUED$	Penalty cost for unserved electric demand [$/MWh]
$CUGD^{IN,Firm}$	Penalty cost for unserved firm gas demand of industrial customers [$/MMSCFD]
D_i	Electric demand at node i, $i \in \mathbf{I}$ [MW]
H_g	Heat rate of gas-fired generator, $g \in \mathbf{G_g}$ [MMSCFD/MWh]
$K_z^{LDC,Int}$	Gas to industrial customers / gas to generators. Both customer types hold interruptible contracts and are connected to LDCs in zone z, $z \in \mathbf{Z}$

$K_z^{Pipe,Int}$	Gas to industrial customers / gas to generators. Both customer types hold interruptible contracts and are connected to pipelines in zone z, $z \in \mathbf{Z}$
$\underline{P_g}, \overline{P_g}$	Minimum and maximum output limit of generator g, $g \in \mathbf{G}$ [MW]
$PTDF_{kij}$	Flow on power transmission line connecting nodes i and j due to a unit injection at node k [%]
T_{ij}	Flow limit on power transmission line connecting nodes i and j, $ij \in \mathbf{L}$ [MW]
$\underline{\Gamma_m}, \overline{\Gamma_m}$	Minimum and maximum gas injection at junction m, $m \in \mathbf{M}$ [MMSCFD]
Θ_{mn}	Resistivity factor of pipeline segment connecting junctions m and n, $mn \in \mathbf{Q}$
$\underline{\Pi_m}, \overline{\Pi_m}$	Minimum and maximum pressure squared at junction m, $m \in \mathbf{M}$ [psi squared]
$\Phi_m^{IN,LDC,Firm}$	Firm contracts held by industrial customers connected to LDCs at junction m, $m \in \mathbf{M}$ [MMSCFD]
$\Phi_m^{IN,Pipe,Firm}$	Firm contracts held by industrial customers connected to pipelines at junction m, $m \in \mathbf{M}$ [MMSCFD]
$\Phi_m^{PP,LDC,Firm}$	Firm contracts held by power plants connected to LDCs at junction m, $m \in \mathbf{M_g^{LDC,Firm}}$ [MMSCFD]
$\Phi_m^{PP,Pipe,Firm}$	Firm contracts held by power plants connected to pipelines at junction m, $m \in \mathbf{M_g^{Pipe,Firm}}$ [MMSCFD]
$\Phi_m^{PP,LDC,Int,Base}$	Served gas demand of power plants holding interruptible contracts and connected to LDCs at junction m in the baseline model, $m \in \mathbf{M}$ [MMSCFD]
$\Phi_m^{PP,Pipe,Int,Base}$	Served gas demand of power plants holding interruptible contracts and connected to pipelines at junction m in the baseline model, $m \in \mathbf{M}$ [MMSCFD]
$\Phi_m^{PP,LDC,Firm,Base}$	Served gas demand of power plants holding firm contracts and connected to LDCs at junction m in the baseline model, $m \in \mathbf{M}$ [MMSCFD]
$\Phi_m^{PP,Pipe,Firm,Base}$	Served gas demand of power plants holding firm contracts and connected to pipelines at junction m in the baseline model, $m \in \mathbf{M}$ [MMSCFD]
$\Phi_m^{RC,LDC,Firm}$	Firm contracts held by LDCs serving residential and commercial customers at junction m, $m \in \mathbf{M}$ [MMSCFD]
Ω_z	Spot price of gas in zone z, $z \in \mathbf{Z}$ [$/MMSCFD]

Variables

p_g	Output of generator g, $g \in \mathbf{G}$ [MW]
u_i	Unserved electric demand at node i, $i \in \mathbf{I}$ [MW]
γ_m	Gas injection at junction m, $m \in \mathbf{M}$ [MMSCFD]
π_m	Pressure squared value at junction m, $m \in \mathbf{M}$ [psi squared]
σ_{mn}	Flow of gas on pipeline segment connecting junctions m and n, $mn \in \mathbf{Q}$ [MMSCFD]
$\tau_z^{PP,Int}$	Cost of gas for power plants holding interruptible contracts in zone z, $z \in \mathbf{Z}$ [$]
$\phi_g^{LDC,Firm}$	Served gas demand of gas-fired generator g holding firm contracts and connected to a LDC, $g \in \mathbf{G_g^{LDC,Firm}}$ [MMSCFD]
$\phi_g^{LDC,Int}$	Served gas demand of gas-fired generator g holding interruptible contracts and connected to a LDC, $g \in \mathbf{G_g^{LDC,Int}}$ [MMSCFD]
$\phi_g^{Pipe,Firm}$	Served gas demand of gas-fired generator g holding firm contracts and connected to a pipeline, $g \in \mathbf{G_g^{Pipe,Firm}}$ [MMSCFD]
$\phi_g^{Pipe,Int}$	Served gas demand of gas-fired generator g holding interruptible contracts and connected to a pipeline, $g \in \mathbf{G_g^{Pipe,Int}}$ [MMSCFD]
$\phi_m^{IN,LDC,Firm}$	Served gas demand of industrial customers holding firm contracts and connected to LDCs at junction m, $m \in \mathbf{M}$ [MMSCFD]
$\phi_m^{IN,LDC,Int}$	Served gas demand of industrial customers holding interruptible contracts and connected to LDCs at junction m, $m \in \mathbf{M}$ [MMSCFD]
$\phi_m^{IN,Pipe,Firm}$	Served gas demand of industrial customers holding firm contracts and connected to pipelines at junction m, $m \in \mathbf{M}$ [MMSCFD]
$\phi_m^{IN,Pipe,Int}$	Served gas demand of industrial customers holding interruptible contracts and connected to pipelines at junction m, $m \in \mathbf{M}$ [MMSCFD]
$\phi_m^{PP,LDC,Firm}$	Served gas demand of power plants holding firm contracts and connected to LDCs at junction m, $m \in \mathbf{M}$ [MMSCFD]
$\phi_m^{PP,LDC,Int}$	Served gas demand of power plants holding interruptible contracts and connected to LDCs at junction m, $m \in \mathbf{M}$ [MMSCFD]

B Test system

This section provides a detailed description of our test system, which is a modified version of the test system in [1]. Power system data and gas system data are obtained from multiple sources, as described in Sections B.1 and B.2, respectively.

B.1 Power System Data

The electric power system includes NYISO (19 nodes), ISO New England (8 nodes), and parts of PJM (2 nodes), Ontario (5 nodes), Quebec (1 node), and the Maritimes (1 node). The nodes are connected by 121 high-voltage transmission lines, some of which have limited transmission capacity. Network data are from [1], who in turn build on [2].

Generators at each node do not correspond to real-world power plants, but represent the total capacity of a given technology and fuel type at a specific network location. Natural gas-fired generating units account for the largest share of generation capacity in our test system (40%): 62% of these plants are single cycle units, while the remaining 38% are combined cycle power plants. Heat rates by technology type are from the Energy Information Administration (EIA) [3], while power output limits are from [1]. As highlighted earlier, gas-fired generators holding interruptible contracts incur fuel costs based on the daily spot price in their respective gas pricing zone (see Fig. 1 in the paper). Other sources of electricity generation capacity include nuclear, hydroelectric (each representing 16% of generation capacity), oil (15%) and refuse (2%). Their power output limits and fuel costs are from [1].

All nodes (except the DC line terminal in Quebec at Chateauguay) have electricity consumption. To parametrize daily load, we rely on data from Federal Energy Regulatory Commission (FERC) Form 714, which provides hourly information by planning area in the U.S. [4]. Most nodes fall into one of three planning areas (ISO New England, NYISO and PJM). Since electricity consumption data for the Canadian provinces are not available, we assign the seven nodes in Canada to the ISO New England planning area. The daily load profiles at each node are obtained as described in the Appendix of [5].

B.2 Gas System Data

The gas system consists of 76 junctions and 92 pipeline segments. Network data are sourced from [1], but we adjust their test system to align it with our gas system modeling framework. Since our focus is on gas availability constraints for power generation due to limited pipeline capacity, we assume no gas infrastructure failures. Therefore, unlike [1], we do not explicitly model gas flow control valves. Additionally, following [6], we classify pipeline segments as active or passive: active segments have compressors between their inlet and outlet junctions, while passive segments do not.

As discussed, a distinctive feature of our model is its consideration of gas consumption by sector and different types of gas contracts. However, these data are not publicly available. Therefore, we estimate the daily scheduled gas deliveries to the residential, commercial, power, and industrial sectors, as well as firm contracts held by power plants and industrial customers. In contrast, we do not estimate interruptible contracts, as in our model gas deliveries to customers holding this contract type are determined by the residual pipeline capacity after serving firm contract holders. As discussed in Section III of the paper, the power and industrial sectors receive interruptible gas based on a daily ratio of deliveries to the two sectors in the same gas pricing zone.

1) Gas deliveries to the residential, commercial, power and industrial sector

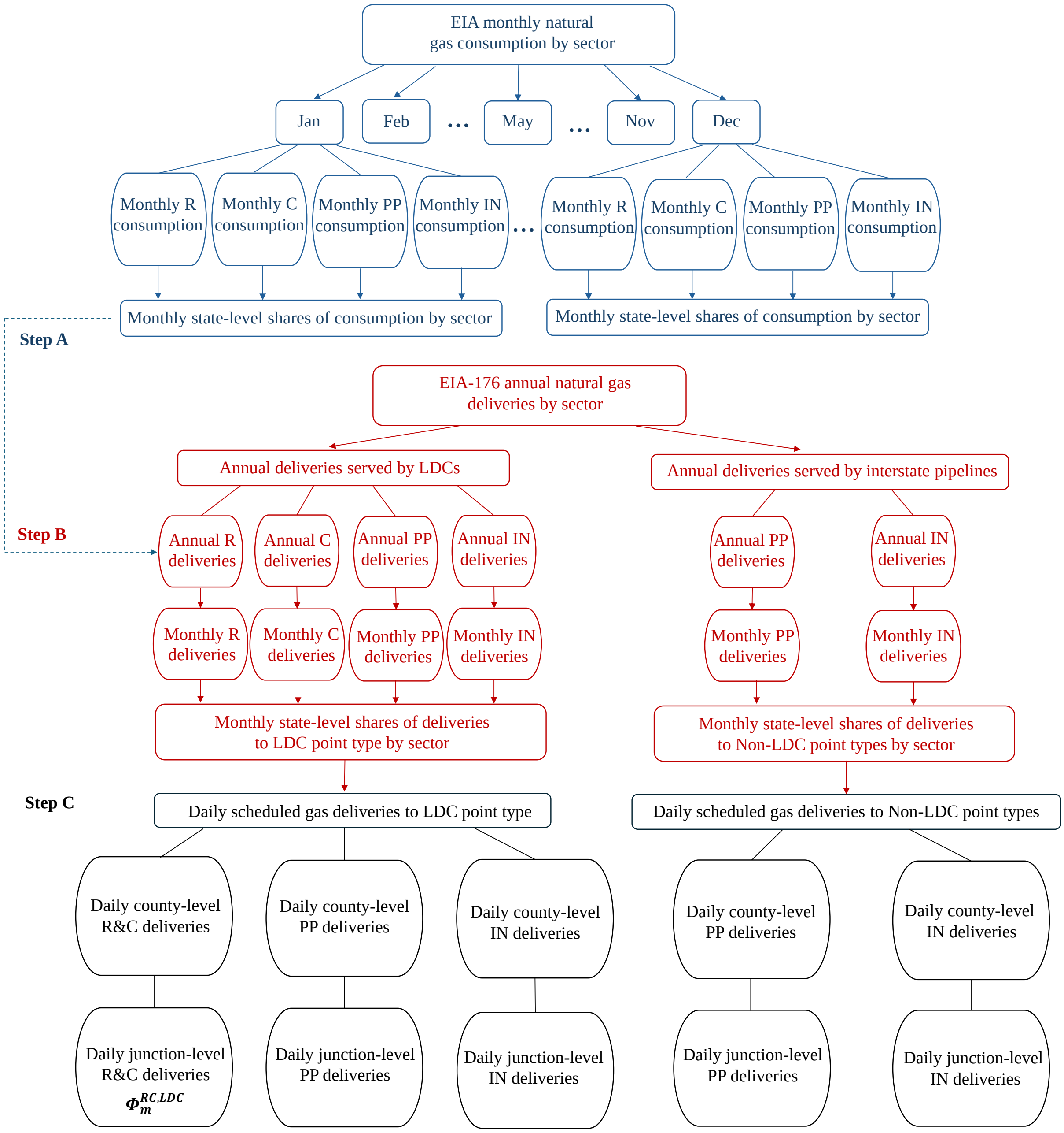
The goal is to estimate scheduled gas deliveries at the junction level by sector (residential, commercial, power plants, and industrial) and interconnection category (LDC and Non-LDC). Interstate pipelines report daily scheduled gas deliveries at various pipeline point types, including LDC Interconnect, End User, and Power Plant. This classification poses some challenges for our modeling purposes because industrial customers and power plants can be connected to multiple point types. LDC Interconnect refers to points where gas is delivered from interstate pipelines to local distribution companies, which primarily serve residential and commercial customers but may also deliver gas to power plants and industrial customers. The End User point type refers to locations where gas is directly delivered to power plants or large industrial customers. The Power Plant point type refers to locations where gas is delivered exclusively to power plants. Since power plants and industrial customers can receive gas from an LDC or from an interstate pipeline, correctly attributing gas deliveries to sectors requires additional data processing and analysis.

As a first step, we classify the three S&P Global point types into two broader interconnection categories: LDC and Non-LDC. The LDC category includes gas deliveries under the LDC Interconnect point type, while the Non-LDC category includes gas deliveries to the End User and Power Plant point types. Next, we estimate monthly state-level shares of gas deliveries by sector and interconnection category using two datasets: EIA's monthly Natural Gas Consumption by End Use [7] and Form EIA-176 [8]. The Natural Gas Consumption by End Use dataset provides monthly state-level gas consumption by sector but does not differentiate between interconnection categories. In contrast, Form EIA-176 reports annual state-level gas deliveries disaggregated by sector and interconnection category. Using the information in these two datasets, we derive monthly state-level shares of gas deliveries by sector and interconnection category. These shares are then applied to daily scheduled gas deliveries from S&P Global to estimate daily scheduled gas deliveries by sector and interconnection category.

Fig. B1 outlines our methodology. As illustrated, the process begins by computing monthly state-level shares of gas consumption by sector using EIA's monthly Natural Gas Consumption by End Use (Step A). These shares are then applied to the annual gas deliveries by sector and interconnection category from Form EIA-176 to obtain monthly state-level gas deliveries. From these volumes, we compute monthly state-level shares of gas deliveries by sector and interconnection category (Step B).

Step C illustrates how we obtain junction-level gas deliveries by sector and interconnection category. First, we obtain daily county-level scheduled gas deliveries at the LDC Interconnect, End User, and Power Plant point types on the 14 interstate pipelines in our study region from S&P Global [9].[1] Next, we group these daily gas deliveries by point of interconnection, and apply the monthly state-level shares from Step B to the daily gas deliveries (assuming that the share remains constant within a month). This yields our estimates for daily county-level gas deliveries by sector and interconnection category. Finally, we assign gas deliveries from the 203 counties in our study region to the 76 junctions in our test system to estimate daily junction-level gas deliveries by sector and interconnection category. Since the number of counties exceeds the number of junctions, we distinguish between two cases: counties without a gas junction (more common) and counties with one or more gas junction (less common). For counties without any gas junctions, we assign gas deliveries to the nearest junction. In contrast, when a county contains more than one gas junction, deliveries are distributed across those junctions in proportion to population.

[1] In our model, scheduled gas deliveries refer to the Intraday 2 nomination cycle, i.e., the final nomination cycle for a given day during our study period. The pipelines included in our study are: Algonquin Gas Transmission, Columbia Gas Transmission, Eastern Gas Transmission and Storage, Eastern Shore Natural Gas Company, Equitrans, Granite State Gas Transmission, Iroquois Gas Transmission System, Maritimes & Northeast Pipeline, Millennium Pipeline Company, National Fuel Gas Supply Corporation, Portland Natural Gas Transmission System, Tennessee Gas Pipeline Company, Texas Eastern Transmission, and Transcontinental Gas Pipeline Company.



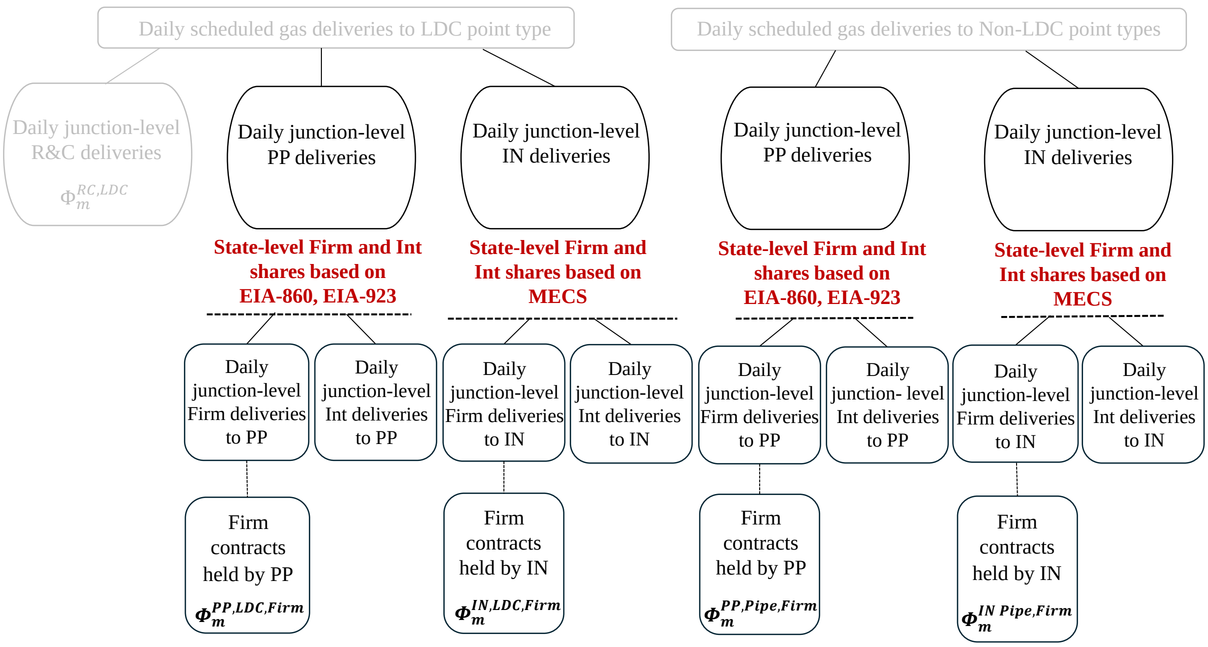
Note: R refers to residential customers, C to commercial customers, PP to power plants, IN to industrial customers. Parameters in our model are shown in bold in the boxes.

Fig. B1: Steps to obtain the daily gas deliveries by sector and interconnection category.

2) Firm contracts held by power plants

Gas deliveries to power plants holding firm contracts are an output of the model and must be bounded by the estimated firm contractual amount. First, Form EIA-860 [10], which collects data on existing U.S. power plants, identifies whether power plants in our study region receive gas through LDCs or directly from interstate pipelines. Next, EIA-923 [11] provides information on natural gas contract types for power plants. We use fuel procurement by contract type in December 2013 to determine state-level shares of firm and interruptible contracts held by power plants in each interconnection category.

We apply these shares to the daily junction-level gas deliveries to power plants by interconnection category from Section *1)*, yielding estimated daily firm and interruptible scheduled gas deliveries at each junction. To estimate the firm contractual amount that power plants hold at each junction, we select the highest estimated daily firm gas deliveries to power plants at that junction in 2013. Fig. B2 provides a visual representation of the steps.



Note: Int refers to interruptible. Parameters in our model are shown in bold in the boxes.

Fig. B2: Steps to obtain the firm and interruptible gas deliveries to power plants and industrial customers.

3) Firm contracts held by industrial customers

Gas deliveries to industrial customers holding firm contracts are also an output of the model and should be constrained by the estimated firm contractual amount. However, unlike power plants, no dataset explicitly categorizes gas contract types and interconnection categories for industrial customers. We infer contract types held by industrial gas customers based on their ability to switch to alternate fuels, based on data provided by EIA's Manufacturing Energy Consumption Survey (MECS) [12]. Specifically, we assume that industrial customers with "switchable" gas consumption hold interruptible contracts. In contrast, industrial customers with "non-switchable" gas consumption are assumed to hold firm contracts - this is because the inability to switch to alternate fuels makes their operations more vulnerable to gas supply disruptions, incentivizing these customers to procure a stable and reliable supply through firm contracts.

Specifically, the MECS provides data on gas consumption across various industrial subsectors. However, MECS data are only available at the national and regional levels and are collected every four years. Using the 2014 dataset, we first calculate the proportion of switchable and non-switchable natural gas usage for each available subsector in the Northeast region. These proportions are then weighted by each subsector's annual GDP contribution within a given state in that region. The shares of firm and interruptible contracts held by industrial customers in a state are obtained by summing the weighted proportions across all subsectors.[2] We apply these shares to the daily junction-level gas deliveries to industrial customers by interconnection category to estimate daily firm and interruptible gas deliveries at each junction. Similar to power plants, the firm contractual amount held by industrial customers at each junction is estimated by identifying the highest daily firm gas deliveries to industrial customers at that junction in 2013.

[2]Unlike power plants, for which the EIA-860 data provides explicit information on the interconnection category, the MECS data does not specify interconnection categories for the industrial subsectors. Therefore, we apply the same firm and interruptible contract shares to both interconnection categories for industrial customers.

C Figures

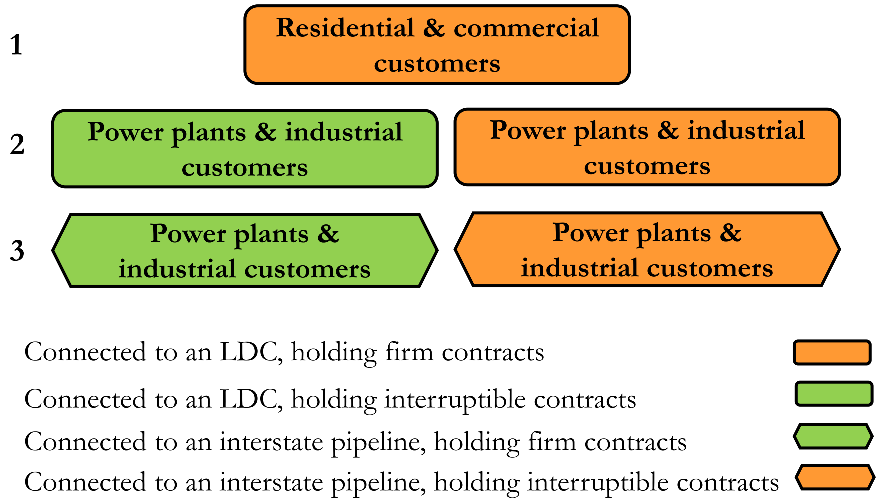


Fig. C1: Existing natural gas curtailment priorities in the event of a gas shortage.

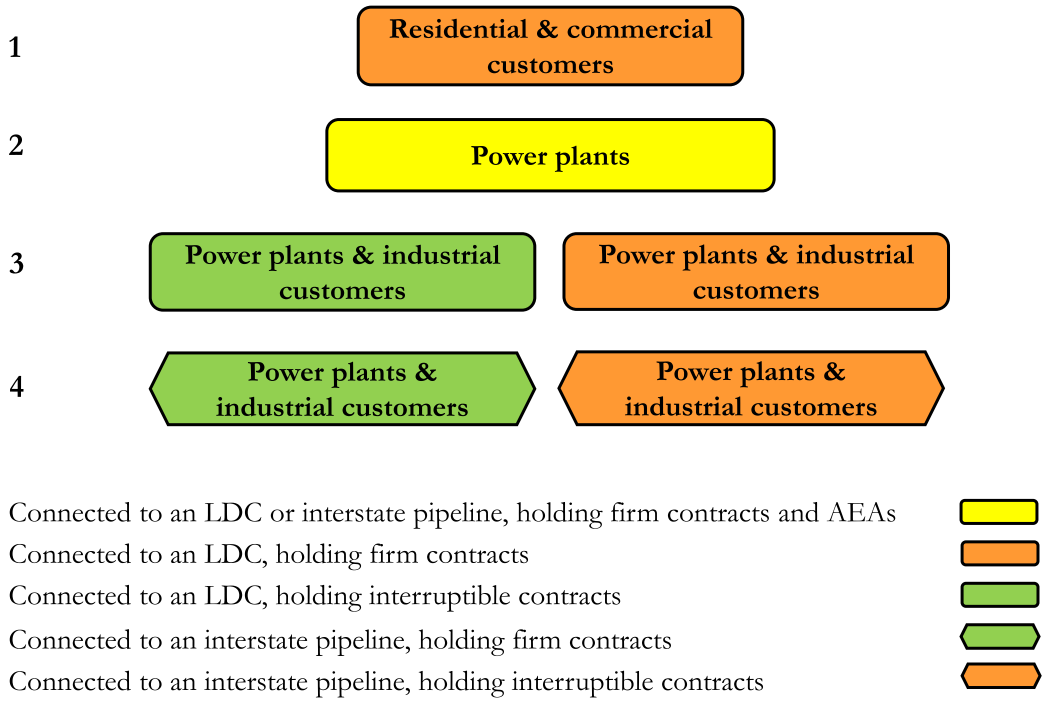


Fig. C2: Alternative natural gas curtailment priorities in the event of a gas shortage.

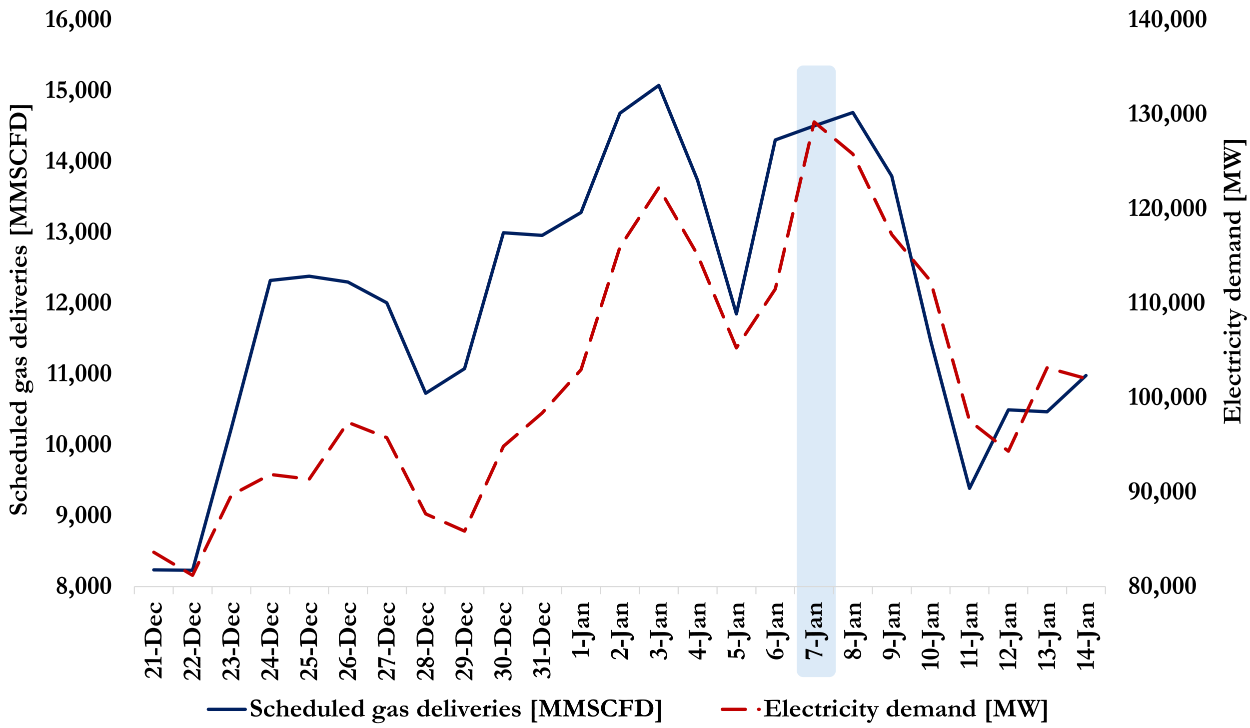
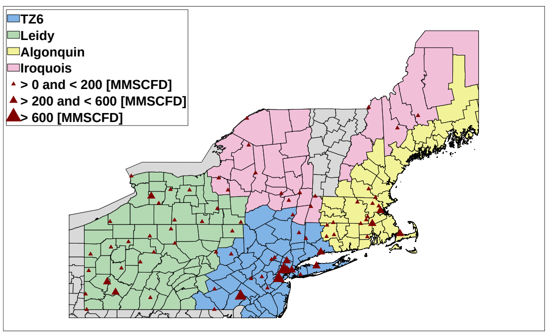
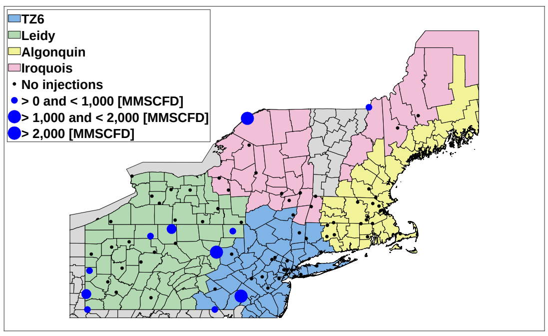


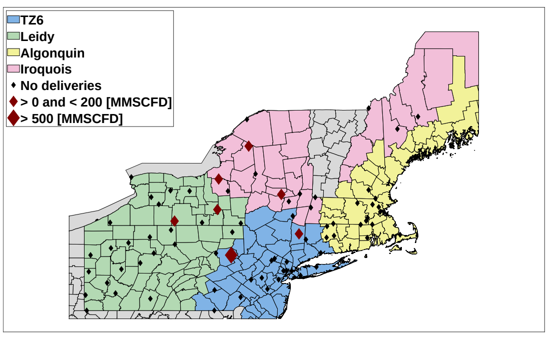
Fig. C3: Daily scheduled gas deliveries and electricity demand across the test system, 25-day period (December 21, 2013 to January 14, 2014).



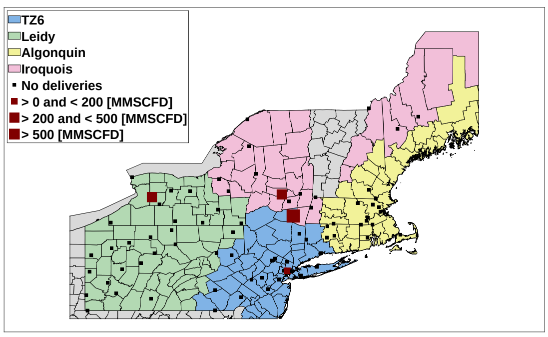
(a) Gas deliveries: residential and commercial.



(b) Gas injections.

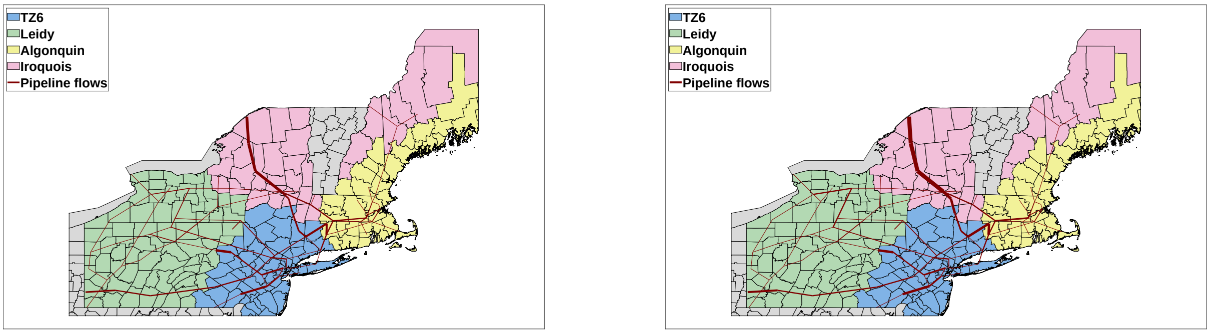


(c) Firm gas deliveries: power plants.



(d) Interruptible gas deliveries: power plants.

Fig. C4: Gas injection and deliveries to residential, commercial customers and power plants, January 7, 2014, Baseline model.



(a) Pipeline flows to serve firm customers.

(b) Pipeline flows to serve all customers.

Fig. C5: Pipeline flows, Baseline model, January 7, 2014.

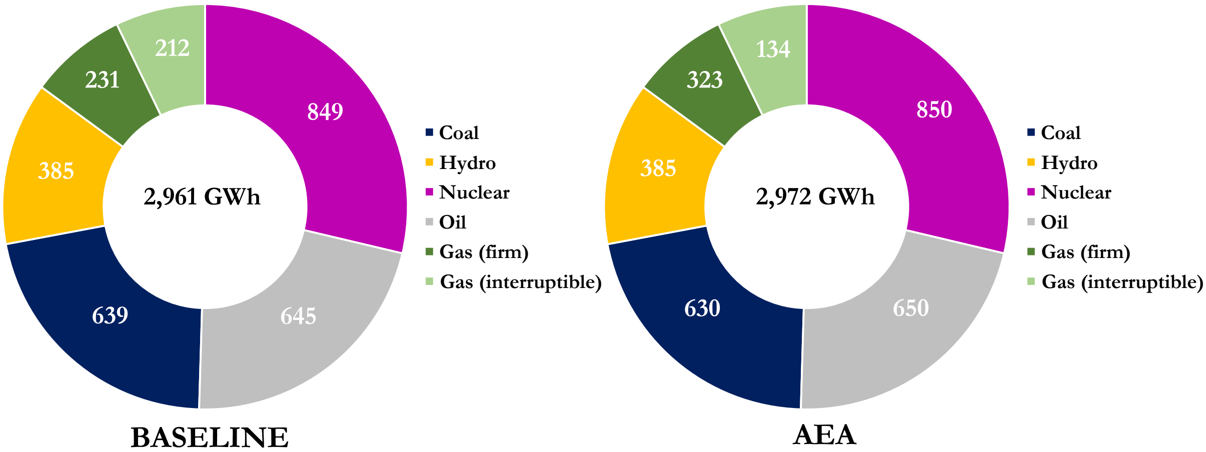
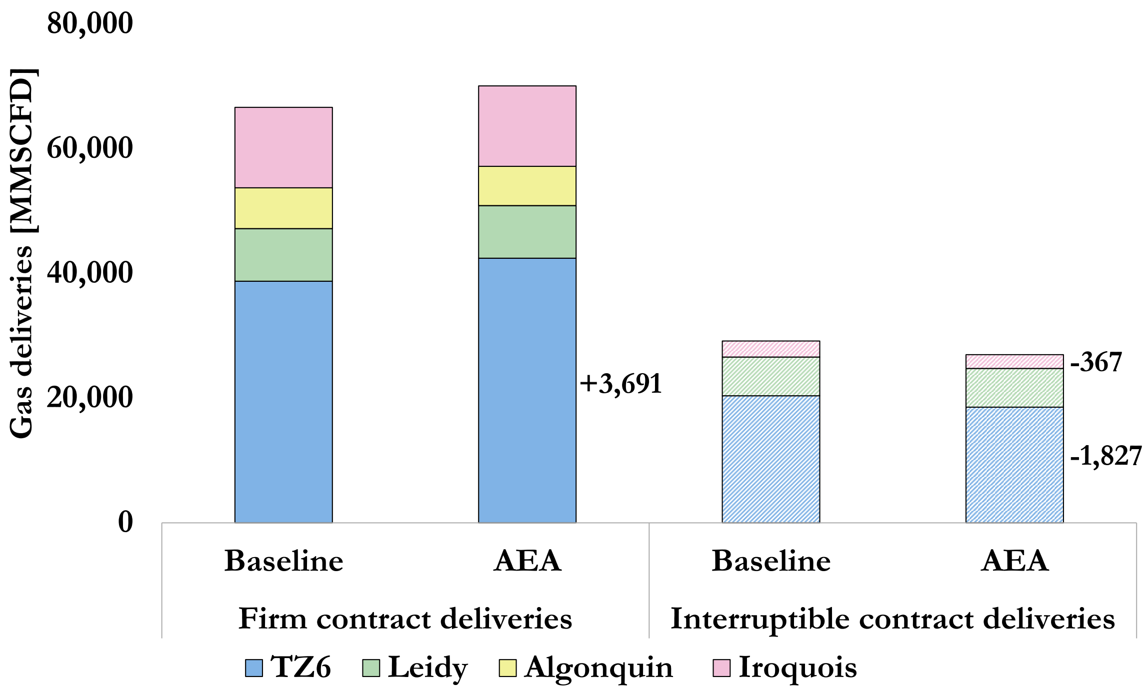


Fig. C6: Generation mix, January 7, 2014, Baseline and AEA models.



Note: Bars without numbers indicate no change relative to the Baseline.

Fig. C7: Power plant gas deliveries by zone and contract type, 25-day period, Baseline and AEA models.

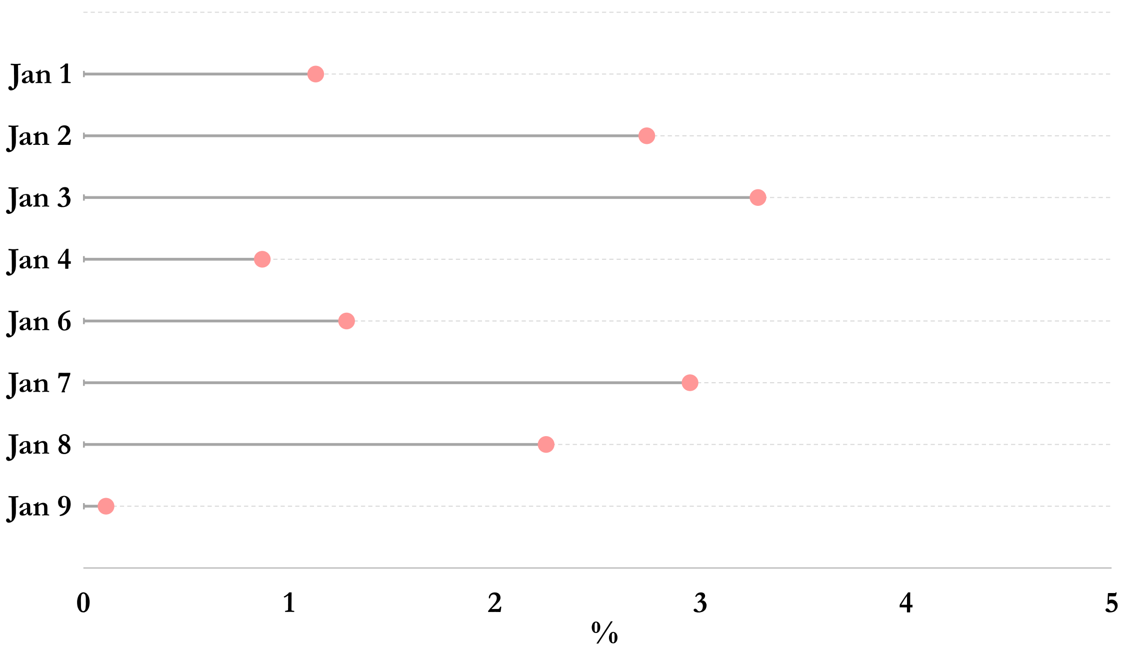


Fig. C8: Unserved electric energy as a percentage of total load, Baseline model, 25-day period.

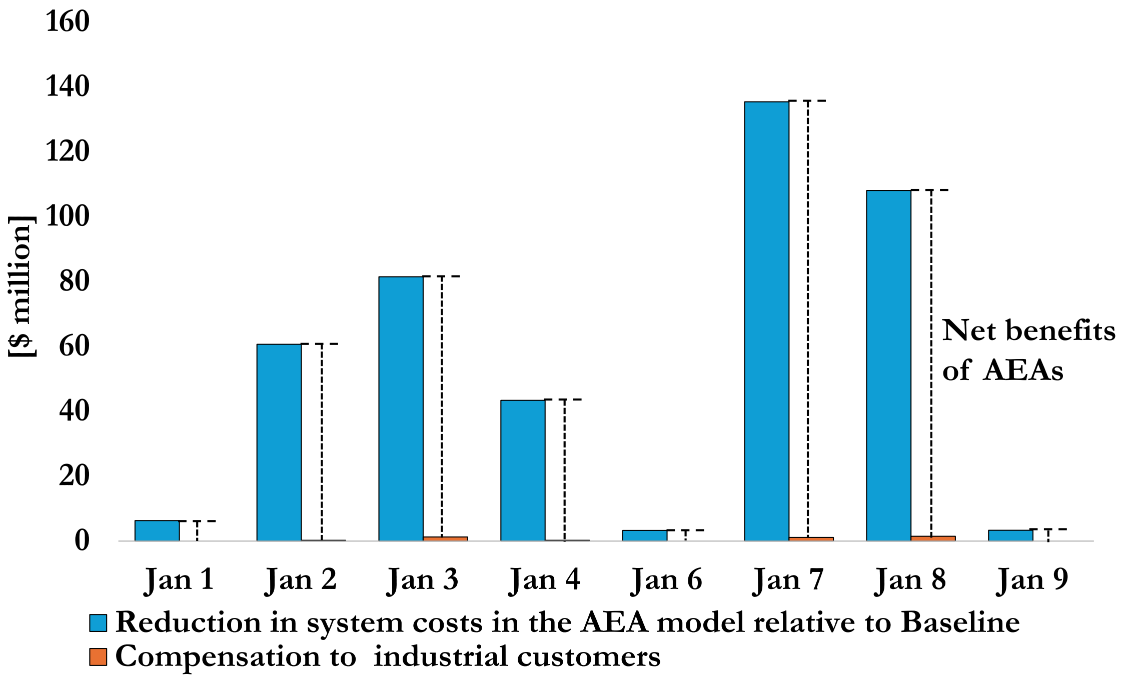


Fig. C9: Reduction in system costs (AEA vs. Baseline models), compensation to industrial customers and net benefits of AEAs (Case A).

D Tables

References

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