A Rolling Horizon Approach for Stochastic MCPs with Endogenous Uncertainty: Application to Gas Markets

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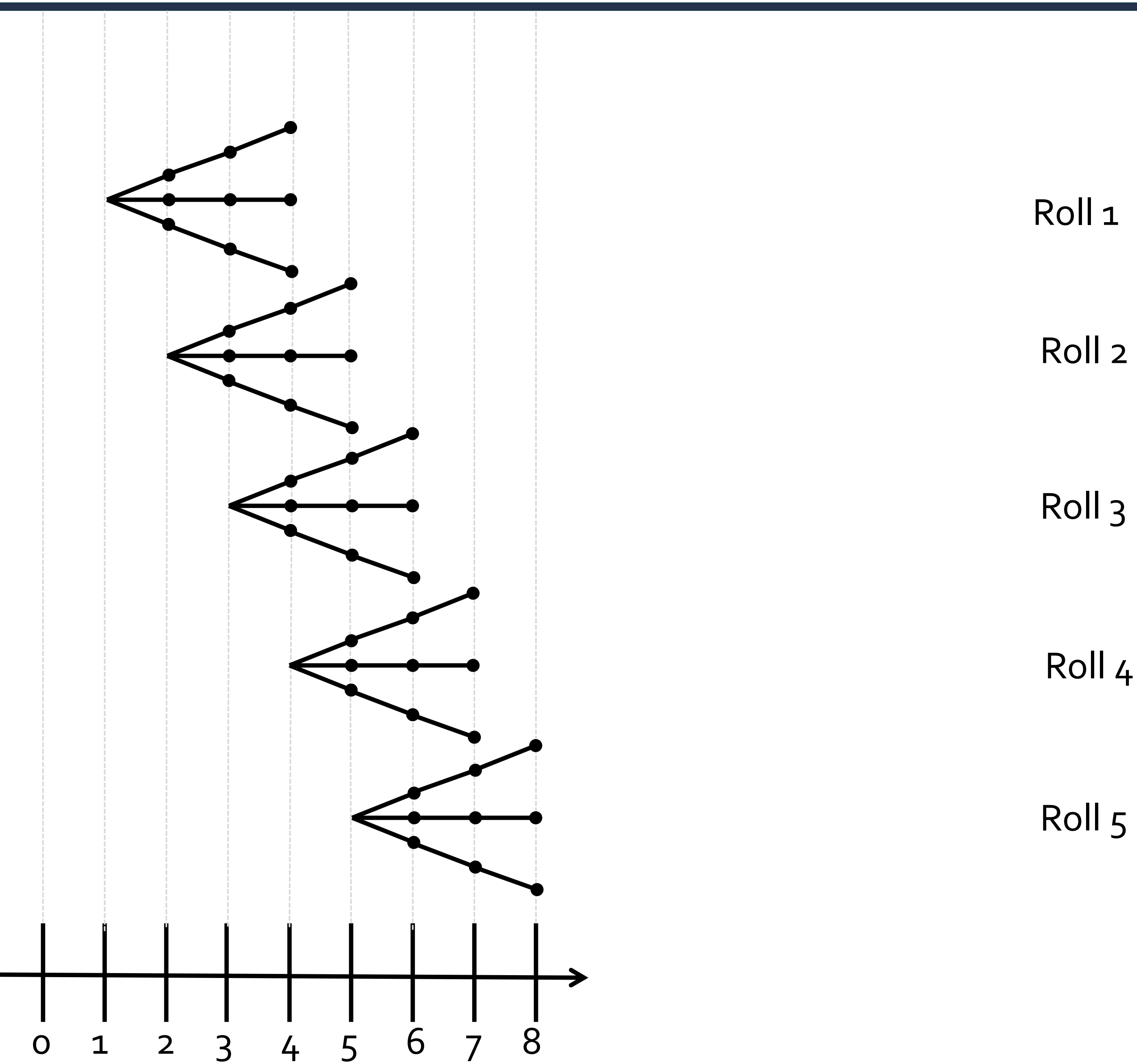
Overview

- Natural gas market model
  - Motivation
  - Rolling horizon model
    - Solving multiple mixed complementarity-based equilibrium models in a sequence
    - Repeated stochastic programming game
  - Multi-player model
    - Gas producers
    - Pipeline system operator
- Results on toy model
  - Benefit of Rolling Horizon – unforeseen stressed demand
  - Learning Algorithm
- Summary and Conclusions

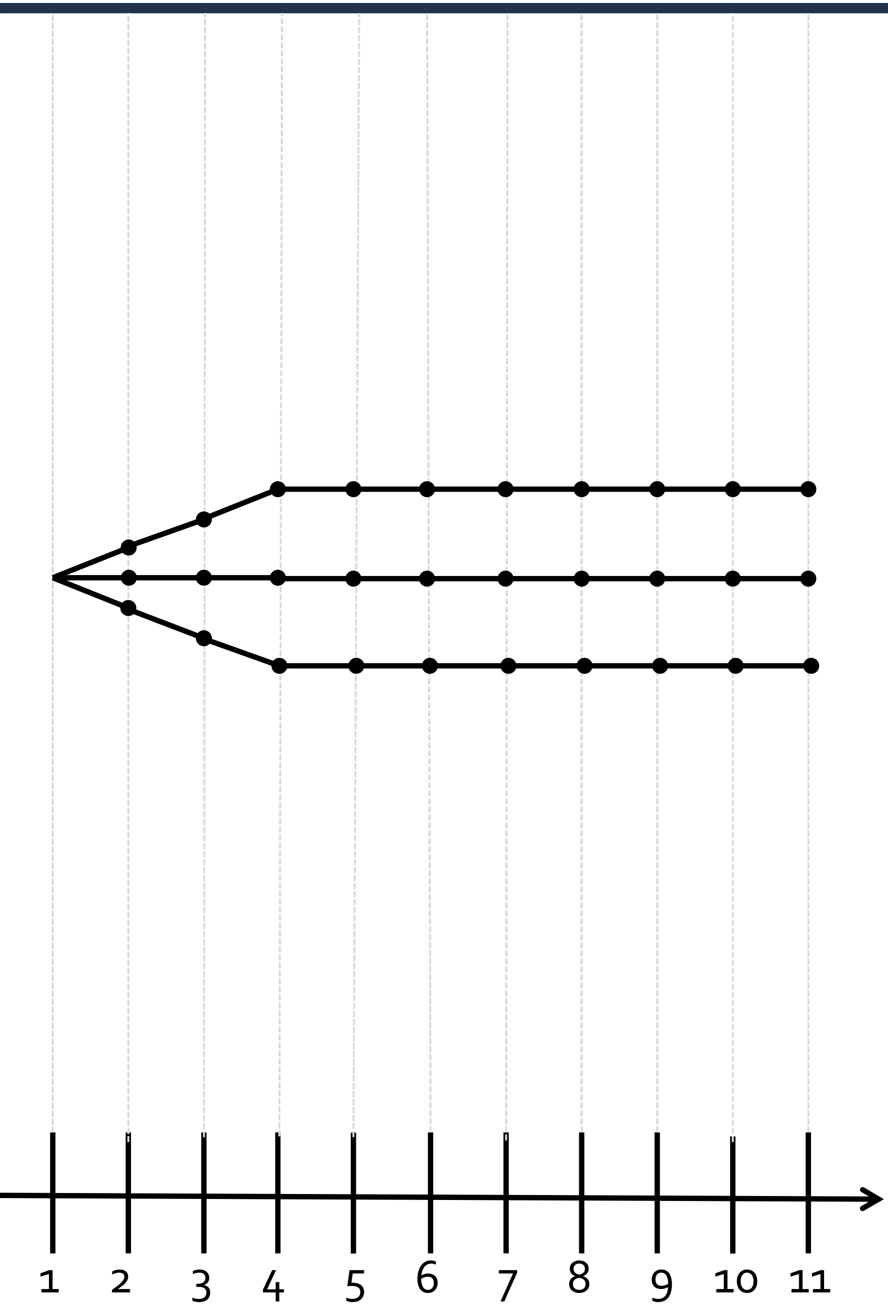
Motivation

- Complementarity-based equilibrium models:
  - Holz, F., von Hirschhausen, C., & Kemfert, C. (2008). *A strategic model of European gas supply (GASMOD)*. Energy Economics, 30(3), 766-788.
  - Lise, W., & Hobbs, B. F. (2008). *Future evolution of the liberalised European gas market: Simulation results with a dynamic model.* Energy, 33(7), 989-1004.
  - Gabriel S.A., Rosendahl, K.E., Egging, R., Avetisyan H., Siddiqui S., (2012). *Cartelization in Gas Markets: Studying the Potential for a 'Gas OPEC'.* Energy Economics, 34(1), 137-152.
- Rolling optimization:
  - **Devine, M. T.**, Gleeson, J. P., Kinsella, J., Ramsey, D. M., (2014). *A Rolling Optimisation Model of the UK Natural Gas Market.* Networks and Spatial Economics, 1-36.
  - Tuohy, A., Meibom, P., Denny, E., & O'Malley, M. (2009). *Unit commitment for systems with significant wind penetration.* Power Systems, IEEE Transactions on, 24(2), 592-601.
- Combined rolling horizon and CBEM not seen before
- Learning algorithms not seen in energy models

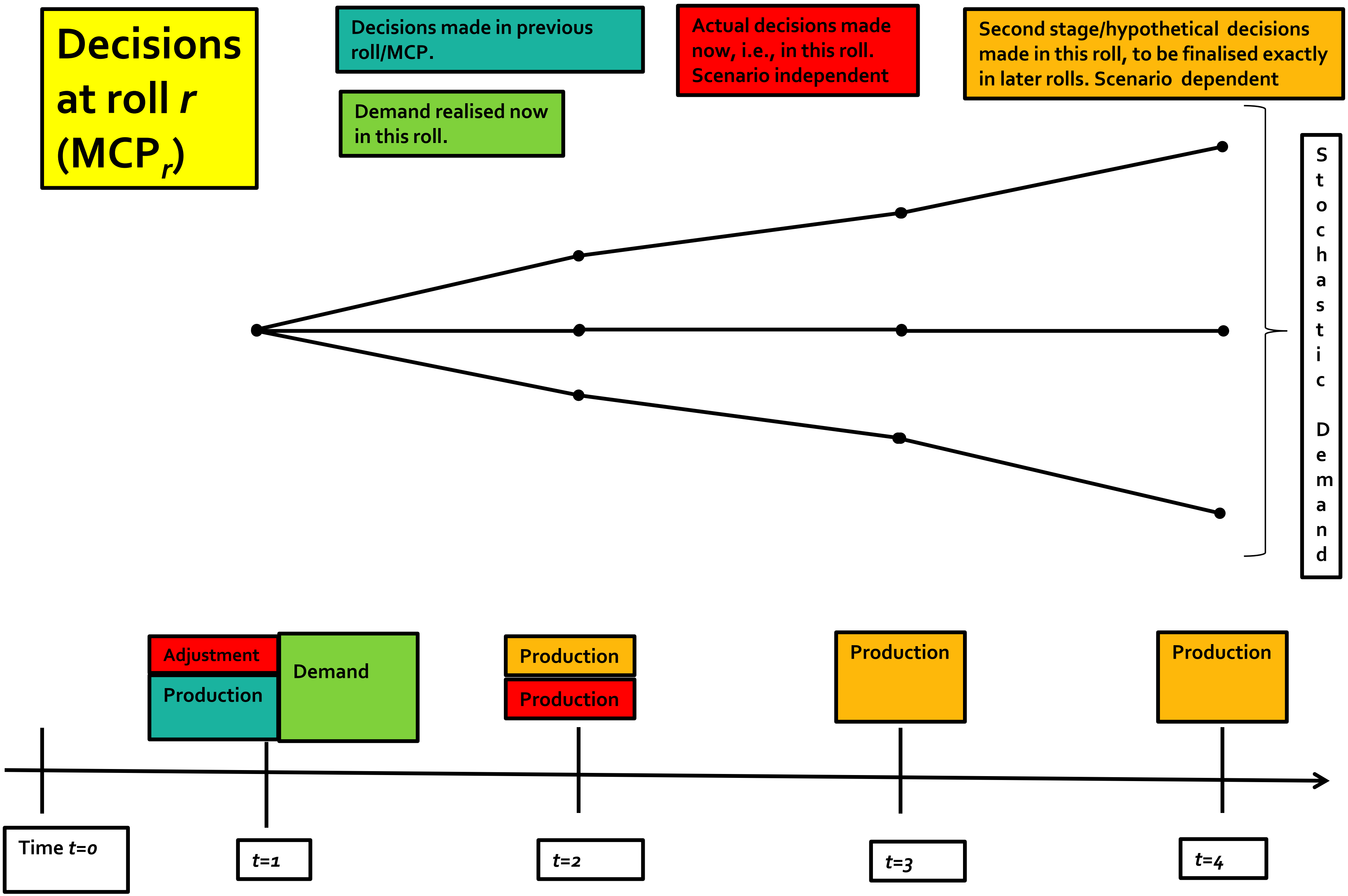
Model: rolling horizon of stochastic demand tree



Single optimisation/equilibrium model



Model: stochastic program



Model: multi-player model

- Gas producers
  - choose sales, production, injection/extraction and flows through pipeline
  - so as to maximize their sales less
    - production costs
    - storage costs
    - pipeline costs
    - cost of adjustments/ recourse costs
  - subject to:
    - production constraints
    - storage constraints
    - adjustment constraints

Model: producer's objective function

$$\max_{sales^*_{pmtr}, prod^*_{pmtr}, flows^{*,prod}_{patr}, inj^*_{pmtr}, xtr^*_{pmtr}} \sum_m \sum_{t=r}^{r+H-1} D_t DAYS_t \Big\{ E_{s(r)} \Big[\pi^s_{mtr} sales^s_{pmtr}$$
$$- C^{production}_{pmtr}(prod^s_{pmtr})$$
$$- \sum_{a \in A(p)} (\tau^{REG}_{at} + \tau^s_{atr}) flows^{s,prod}_{patr} - C^{storage}_{pmtr}(inj^s_{pmtr}, xtr^s_{pmtr}) \Big] \Big\}$$
$$- D_{t=r} DAYS_{t=r} \Big(RU^{prod}_{pmr} prod^{adj+}_{pm(t=r)r} + RO^{prod}_{pmr} prod^{adj-}_{pm(t=r)r}$$
$$+ RU^{sales}_{pmr} sales^{adj+}_{pm(t=r)r} + RO^{sales}_{pmr} sales^{adj-}_{pm(t=r)r}$$
$$+ RU^{inj}_{pmr} inj^{adj+}_{pm(t=r)r} + RO^{inj}_{pmr} inj^{adj-}_{pm(t=r)r}$$
$$+ RU^{xtr}_{pmr} xtr^{adj+}_{pm(t=r)r} + RO^{xtr}_{pmr} xtr^{adj-}_{pm(t=r)r}$$
$$+ \sum_{a \in A(p)} (RU^{flows}_{par} flows^{adj+,prod}_{pa(t=r)r} + RO^{flows}_{par} flows^{adj-,prod}_{pa(t=r)r}) \Big)$$
$$- D_{t=r+1} DAYS_{t=r+1} E_{s(r)} \Big[RU^{prod}_{pmr} prod^{SS+,s}_{pm(t=r+1)r}$$
$$+ RO^{prod}_{pmr} prod^{SS-,s}_{pm(t=r+1)r}$$
$$+ RU^{sales}_{pmr} sales^{SS+,s}_{pm(t=r+1)r} + RO^{sales}_{pmr} sales^{SS-,s}_{pm(t=r+1)r}$$
$$+ RU^{inj}_{pmr} inj^{SS+,s}_{pm(t=r+1)r} + RO^{inj}_{pmr} inj^{SS-,s}_{pm(t=r+1)r}$$
$$+ RU^{xtr}_{pmr} xtr^{SS+,s}_{pm(t=r+1)r} + RO^{xtr}_{pmr} xtr^{SS-,s}_{pm(t=r+1)r}$$
$$+ \sum_{a \in A(p)} (RU^{flows}_{par} flows^{SS+,s,prod}_{pa(t=r+1)r} + RO^{flows}_{par} flows^{SS-,s,prod}_{pa(t=r+1)r}) \Big]$$

Expected sales less cost

Adjustment costs

2nd stage recourse costs

Model: multi-player model

- Pipeline system operator:
  - choose pipeline flows between nodes/markets
  - so as to maximize their sales less
    - pipeline flows costs
    - cost of adjustments/ recourse costs
  - subject to:
    - pipeline constraints
    - adjustment constraints
- Market clearing conditions:
  - Total sales = demand
  - Amount of gas flowing through pipelines is balanced

Model: multi-player model

Pipeline system operator’s objective function:

$$\max_{flow^{*,tso}_{atr}} \sum_a \left\{ \sum_{t=r}^{r+H-1} D_t DAYS_t E_{s(r)} \left[(\tau^s_{atr} + \tau^{REG}_{at}) flows^{s,tso}_{atr} - C^a(flows^{s,tso}_{atr}) \right] \right.$$

$$- D_{t=r} DAYS_{t=r} (RU^{flows}_{ar} flows^{adj+,tso}_{a(t=r)r} + RO^{flows}_{ar} flows^{adj-,tso}_{a(t=r)r})$$

$$\left. - D_{t=r+1} DAYS_{t=r+1} E_{s(r)} \left[RU^{flows}_{ar} flows^{SS+,s,tso}_{a(t=r+1)r} + RO^{flows}_{ar} flows^{SS-,s,tso}_{a(t=r+1)r} \right] \right\}$$

Expected sales less cost

Adjustment costs

2nd stage recourse costs

Market clearing conditions:

$$flows^{s,tso}_{atr} = \sum_p flows^{s,prod}_{patr} \ \forall s, a, t \quad (\tau^s_{atr})$$

Flow balancing

$$\sum_p DAYS_t sales^s_{pmtr} = Z^s_{mr} - B^s_{mr} \pi^s_{mtr} \forall s, m, t \quad (\pi^s_{mtr})$$

Supply and demand balancing

Mixed Complementarity-Based Equilibrium Model

- Given a function $F: \boldsymbol{R}^{\boldsymbol{n}} \rightarrow \boldsymbol{R}^{\boldsymbol{n}}$, and lower and upper bounds $l \in \{\boldsymbol{R} \cup \{-\infty\}\}^{\boldsymbol{n}}$, $u \in \{\boldsymbol{R} \cup \{\infty\}\}^{\boldsymbol{n}}$.
- The mixed complementarity problem is to find $x \in \boldsymbol{R}^{\boldsymbol{n}}$ such that one of the following holds for each $i \in \{1, \ldots, n\}$:

$$F_i(x) = 0 \; and \; l_i \leq x_i \leq u_i,$$

$$F_i(x) > 0 \; and \; x_i = l_i,$$

$$F_i(x) < 0 \; and \; x_i = u_i.$$

See: Gabriel, S. A., et al. *Complementarity modeling in energy markets*. Vol. 180. Springer, 2012.

- For each roll of this problem:

$$F(x) = \begin{bmatrix} KKT \; optimality \; conditions \; for \; producers \\ KKT \; optimality \; conditions \; for \; TSO \\ Market \; clearing \; conditions \end{bmatrix}$$

Model

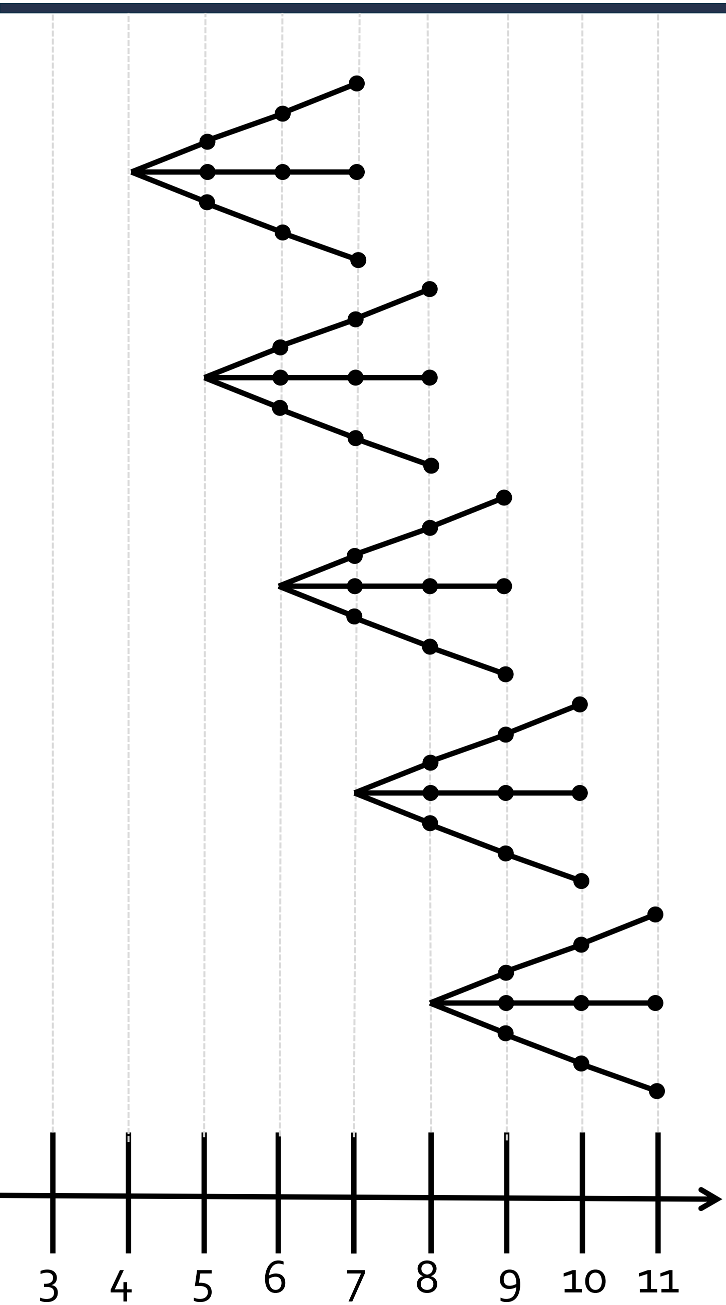
- Update rules:
  - Storage: injections and extractions from previous roll used to update amount of gas in storage
  - Demand horizon rolls forward one period
  - Production capacities reduced by amount produced in previous roll
  - Learning algorithms
- Data: three-node toy model
  - Node 1: New Jersey, New York and Pennsylvania
  - Node 2: Illinois, Indiana, Michigan, Ohio, Wisconsin
  - Node 3: Delaware, District of Columbia, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia, West Virginia

Results

- Stressed demand in time 7

- Learning algorithm

Base case(no stress on demand)



Roll 4

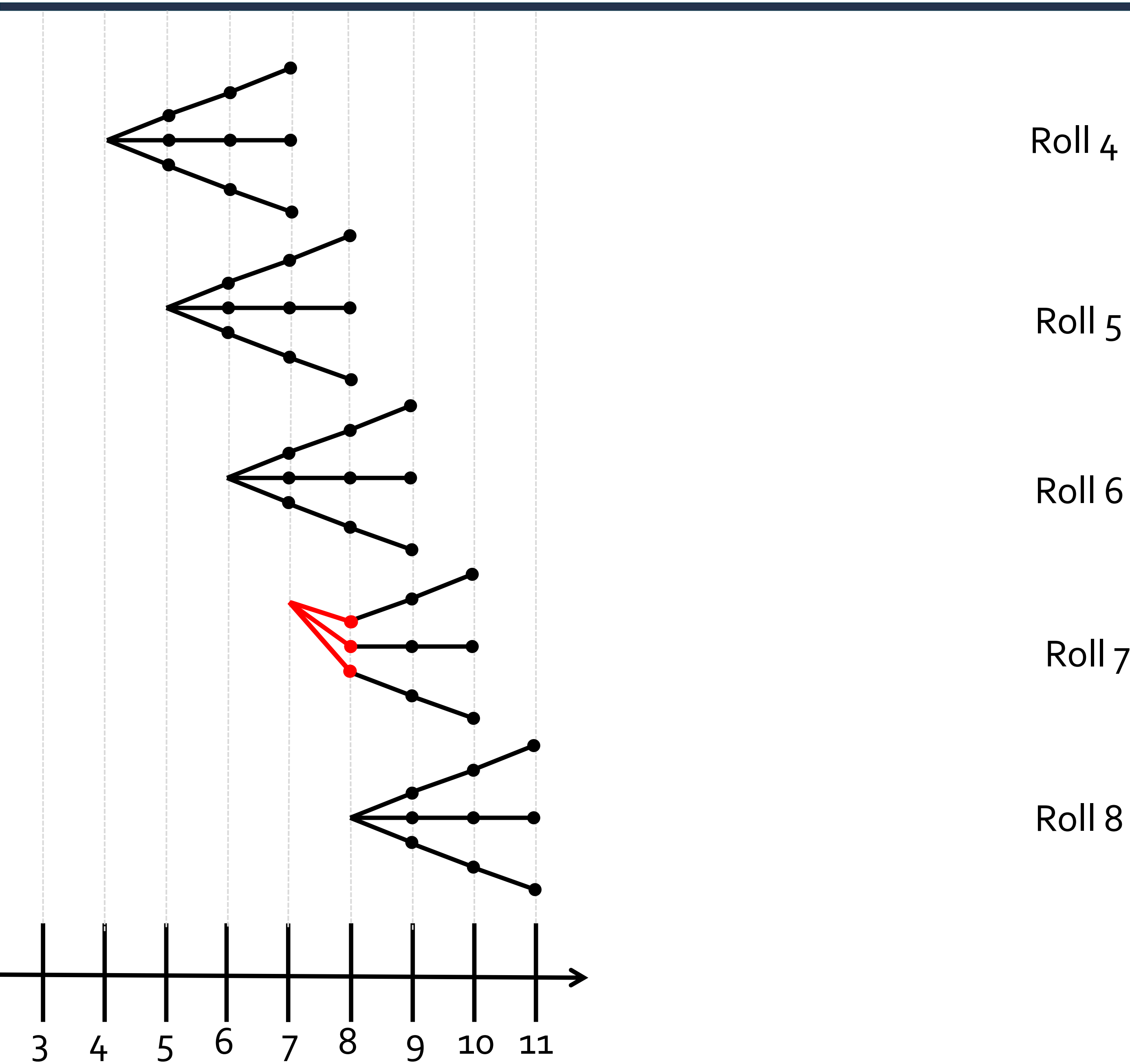
Roll 5

Roll 6

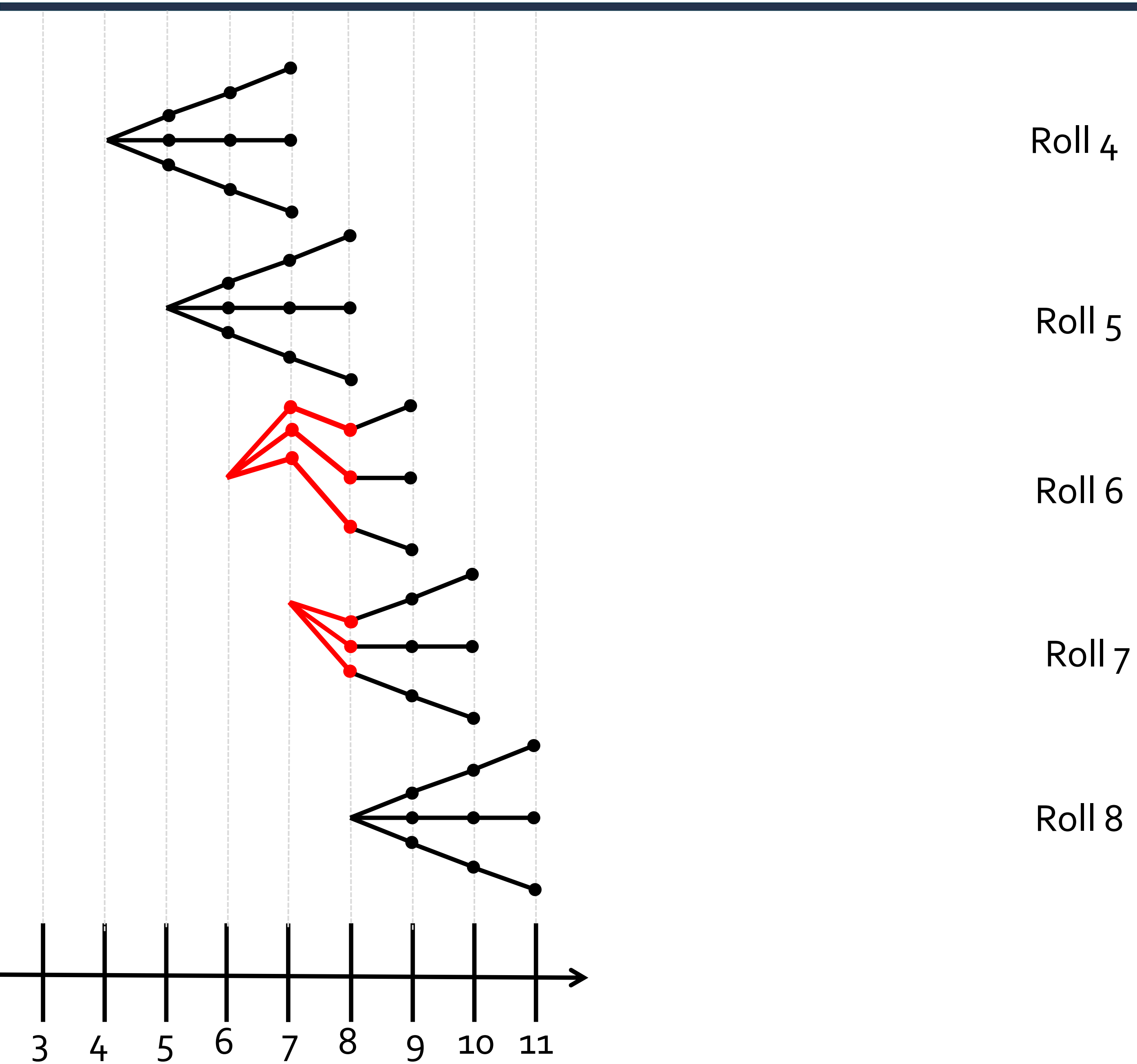
Roll 7

Roll 8

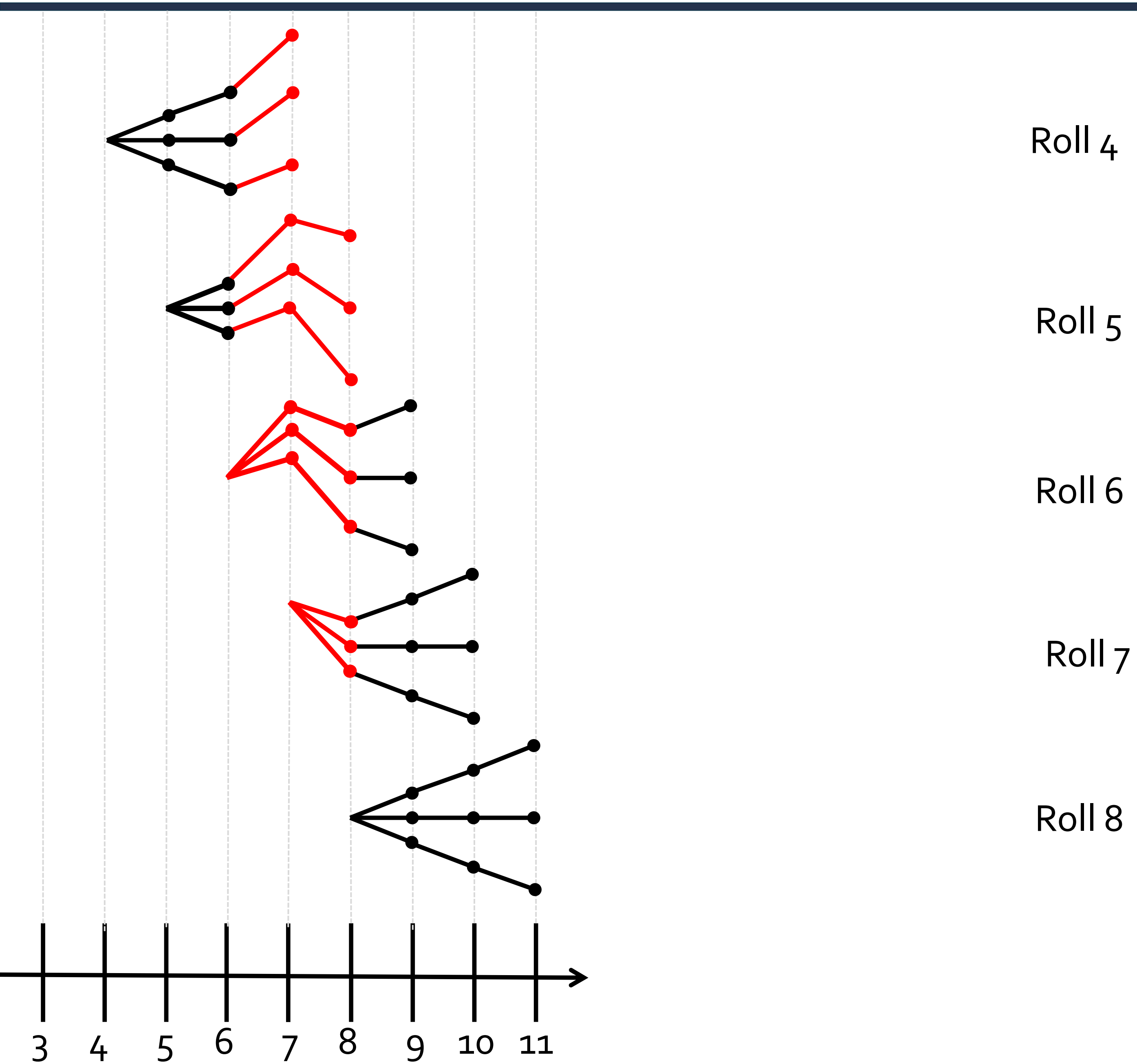
Stressed demand: no foresight



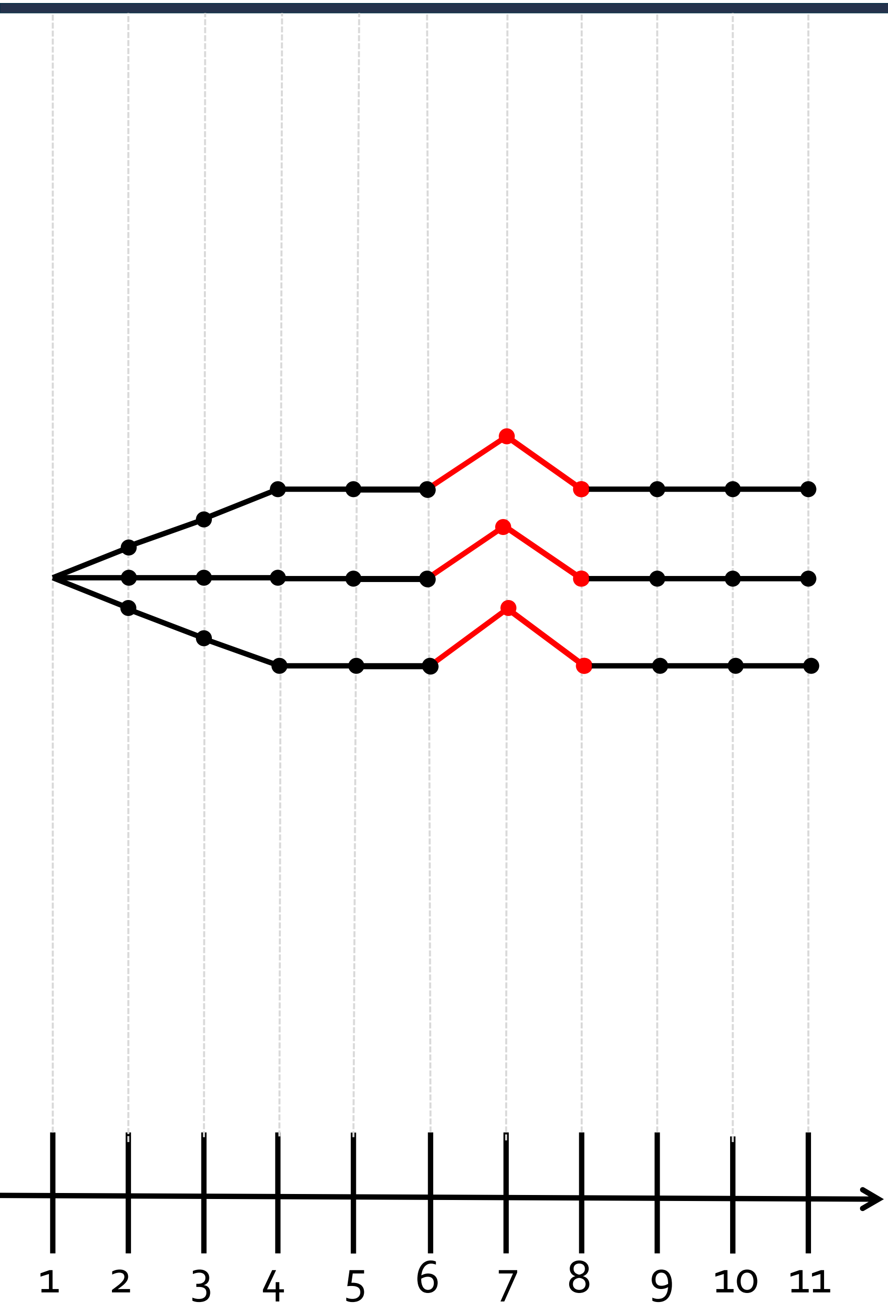
Stressed demand: one period ahead foresight



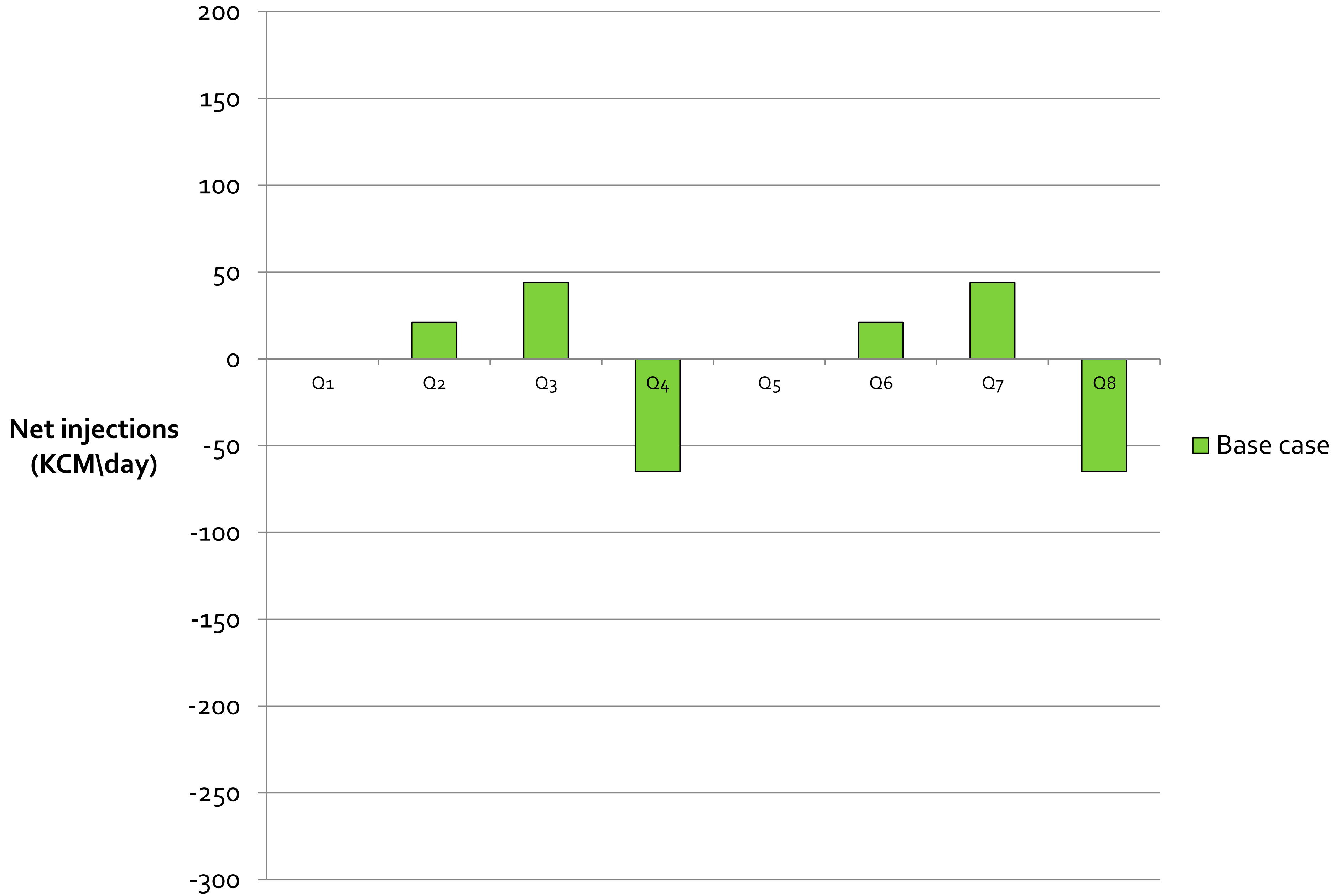
Stressed demand: three periods ahead foresight



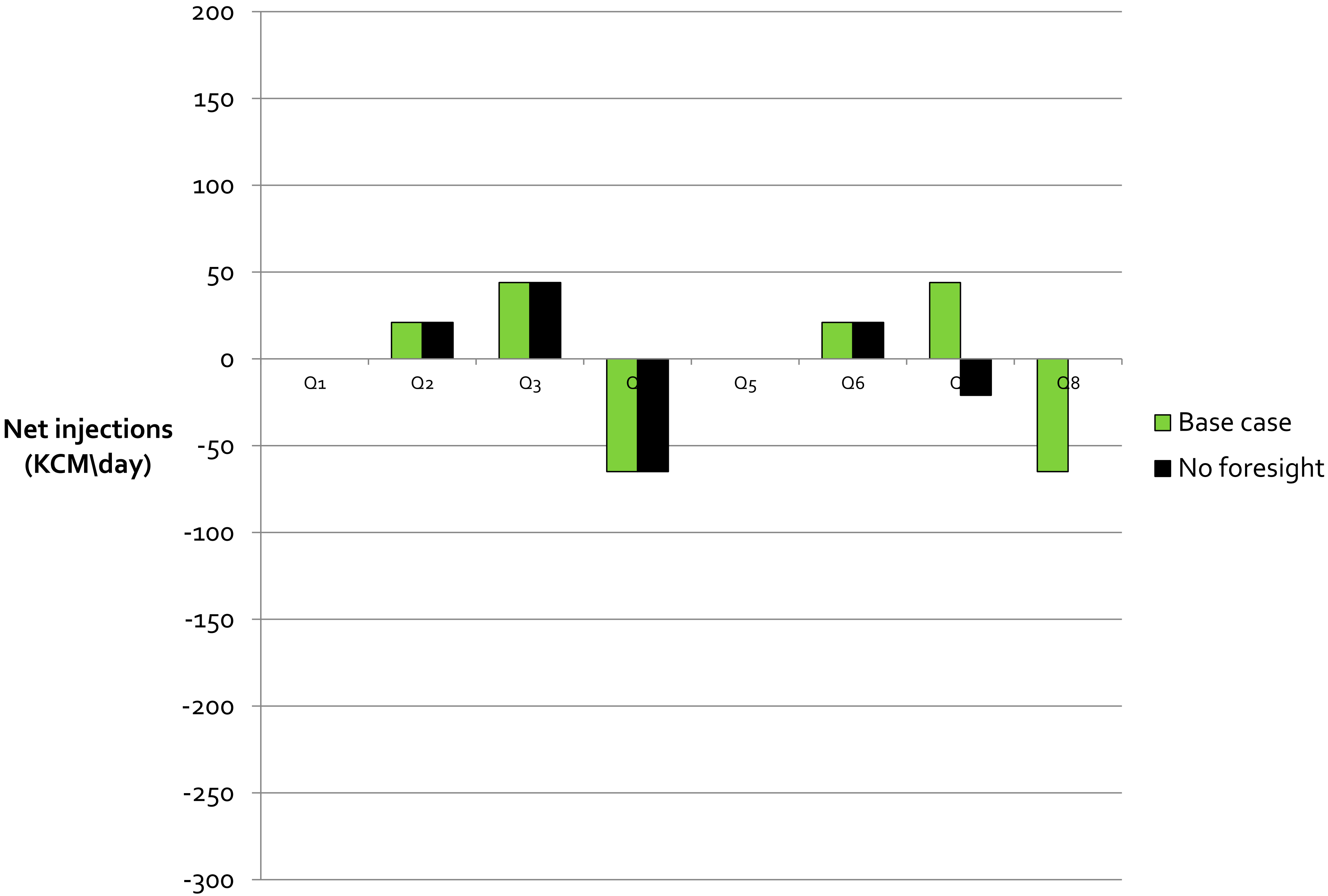
Stressed demand: perfect foresight



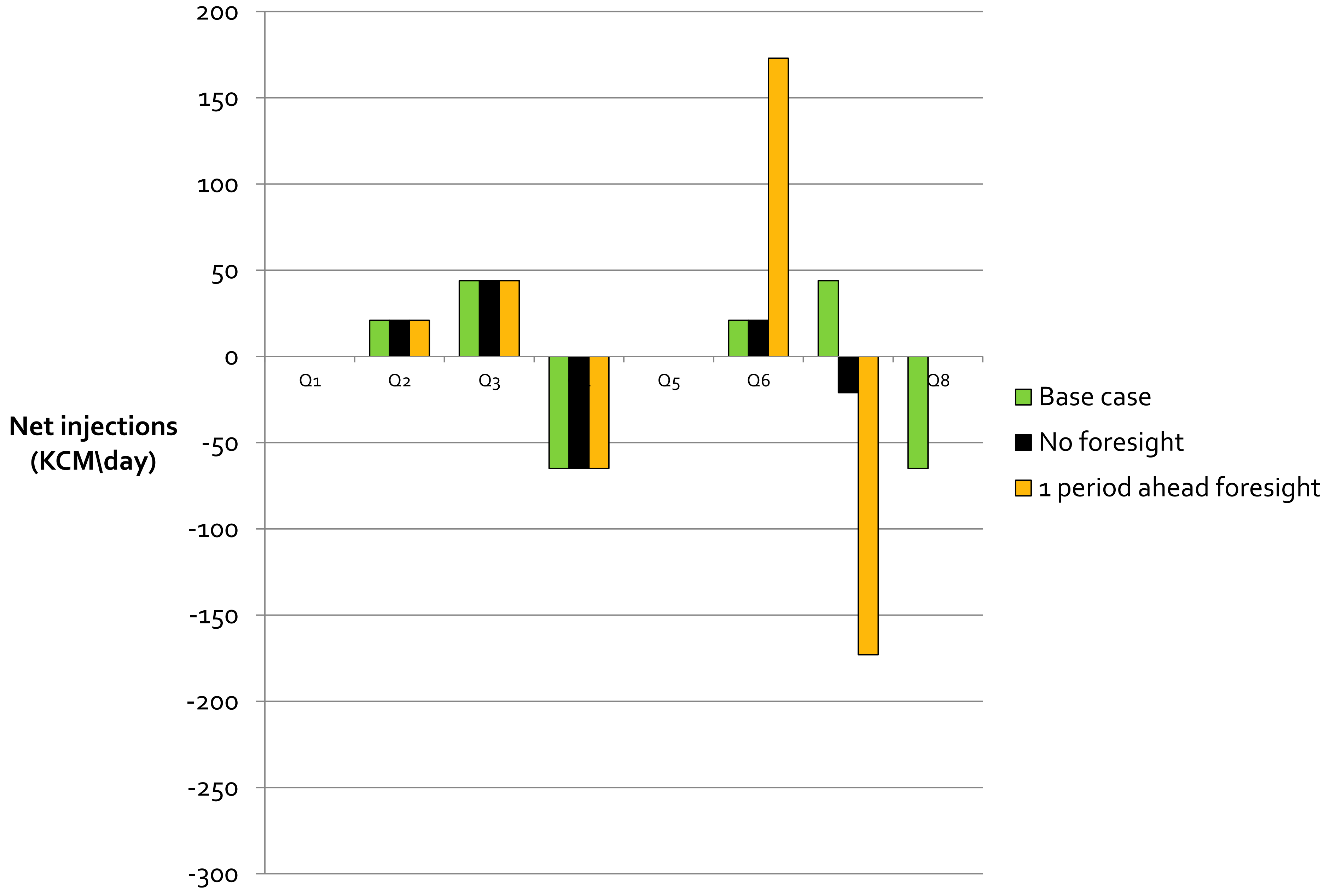
Benefits of rolling horizon: stressed demand in roll 7



Benefits of rolling horizon: stressed demand in roll 7



Benefits of rolling horizon: stressed demand in roll 7



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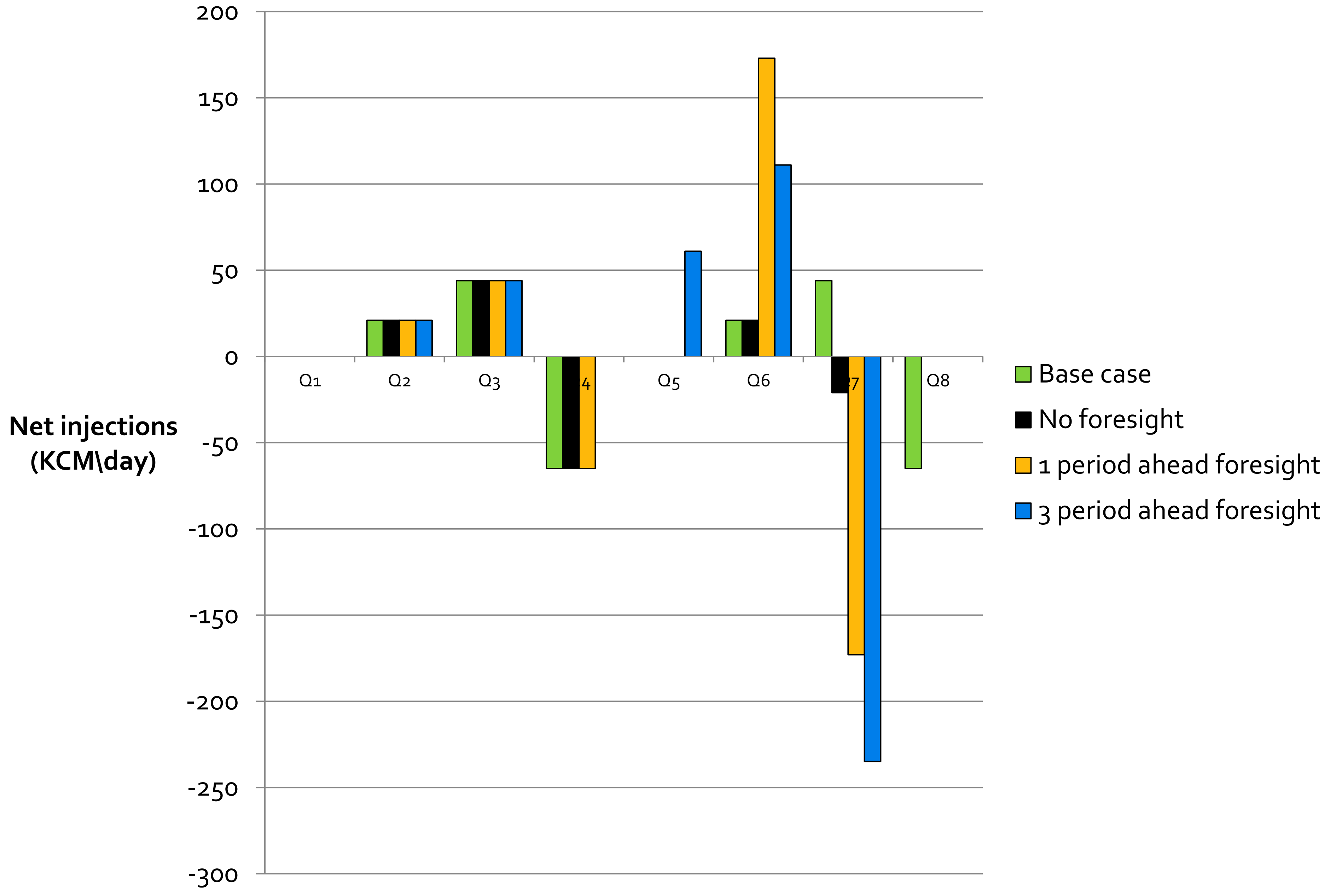
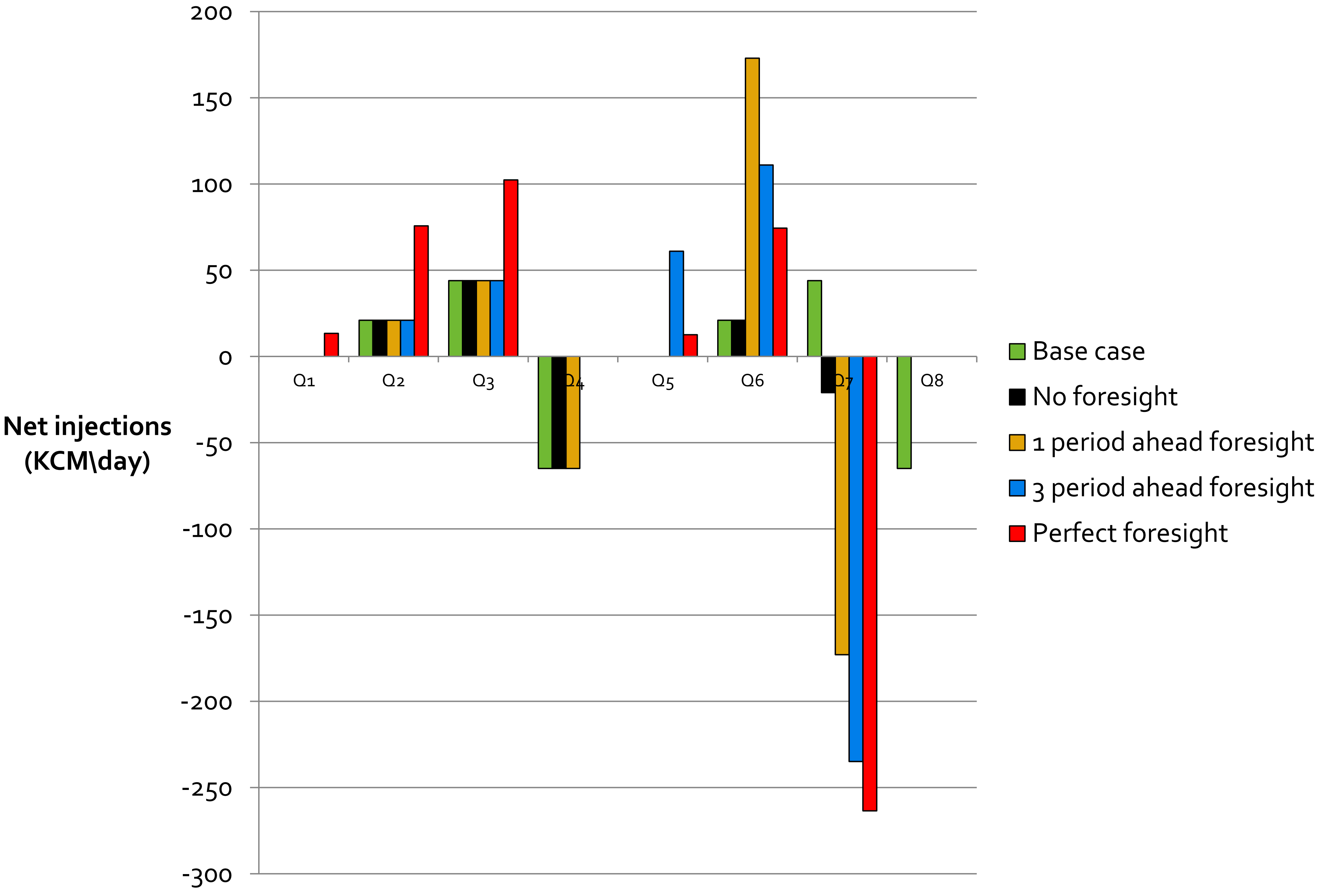
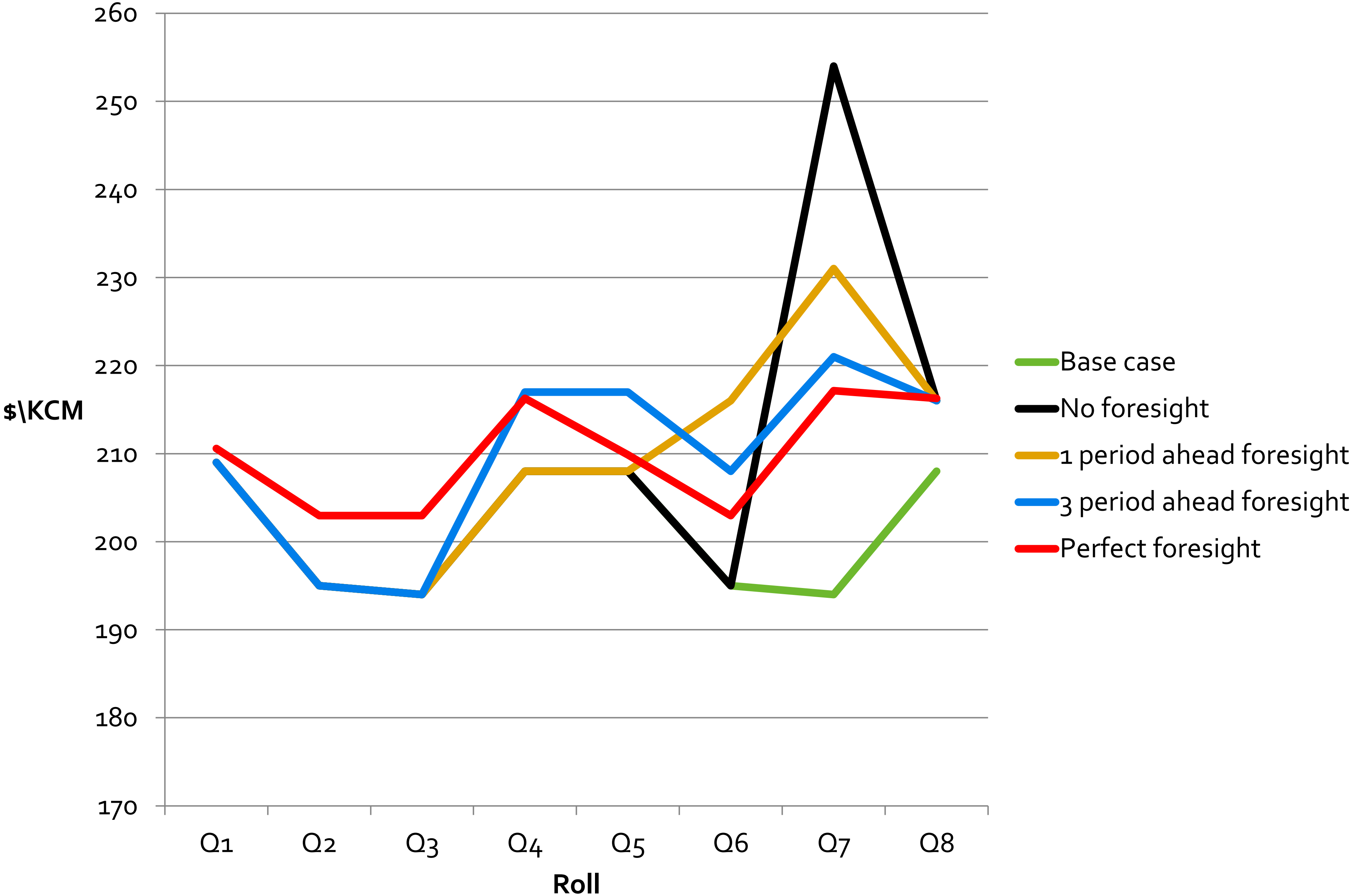


Benefits of rolling horizon: stressed demand in roll 7



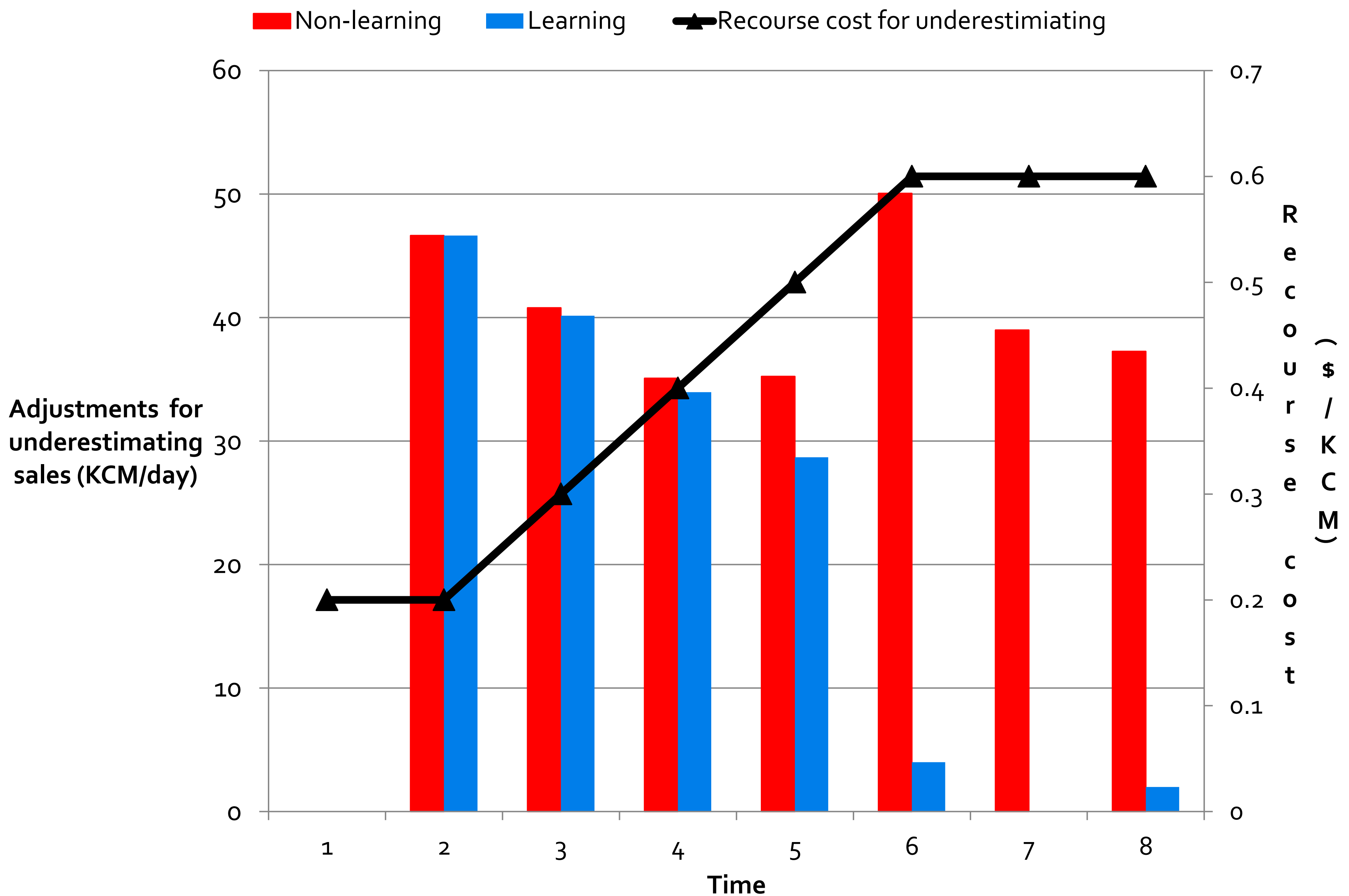
Benefits of rolling horizon: stressed demand in roll 7



Learning algorithms

- Allow models to incorporate changing risk preferences and probabilities over time
- Example:
  - After each roll check:
  - ***IF*** First-Stage decisions for Sales over-estimate for actual demand
    - ***Then*** increase recourse cost associated over-estimating demand/production
  - ***ELSE IF*** First-Stage decisions for Sales under-estimate actual demand
    - ***Then*** increase recourse cost associated under-estimating demand/production
- Other algorithms based on profits

Endogenous uncertainty



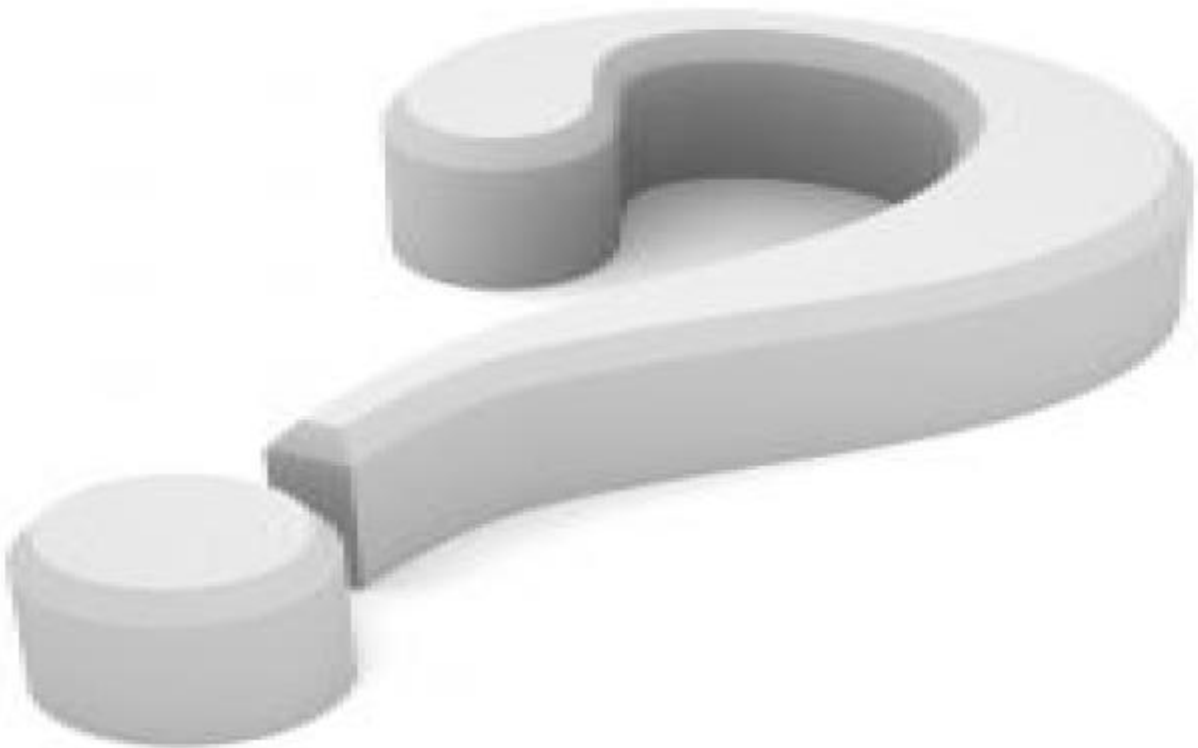
Other projects

- Renewable Energy Feed-In Tariffs
  - Farrell, N., **Devine, M.T.**, Lee, W.T., Gleeson, J.P., Lyons, S., *Specifying an Efficient Renewable Energy Feed-in Tariff, MPRA Working Paper No. 49777*, 2013 and under review.
  - **Devine, M.T.**, Farrell, N., Lee, W.T., *Managing investor and consumer exposure to electricity market price risks through Feed-in Tariff design.* Under review.
- Simulation model of shipping process with Rusal Aughinish
  - Cimpeanu, R., **Devine, M.T,** Tocher, D., Clune, L., *Development and optimization of a Port Terminal Loader Model at RUSAL Aughinish.* Accepted to Simulation Modelling, Practise and Theory

Summary and conclusions

- Introduced rolling horizon mixed complementarity-based equilibrium model of natural gas market
  - Multi-player model
  - Repeated game
  - Stochastic program
- Described the benefits of rolling horizon in the situation of unforeseen stressed demand
- Examined the effects of a learning algorithm on a natural gas market model
- Rolling horizons and learning can add realism to gas market model models

Questions



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