CBE 750 Course Project

Optimization Model for Operating Battery Systems in Multi-Level Electricity Markets

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Problem Statement

- Aim: To operate a battery system in a multi-level electricity market to maximize the daily revenues
- Battery systems can be integrated in a power grid to provide energy and regulation services
- Two components of revenues considered:
  - Energy sale: Battery provides net power to the grid and the grid pays the battery for the amount of energy sold
  - Providing regulation capacity or “band”: Grid pays the battery for providing a “band” around mean power within which grid can regulate net power output from battery
- Energy sale is organized in a three level market while regulation market has two levels
- Net battery power can be negative when the battery is drawing power from grid to recharge
- Problem is formulated as a deterministic linear program
- A comparison of ~~monthly~~ yearly revenues will be made by solving the optimization problem with two approaches:
  - Rolling horizon of 1 day
  - Solving complete optimization problem for 1 ~~month~~ year

Battery Operation Model

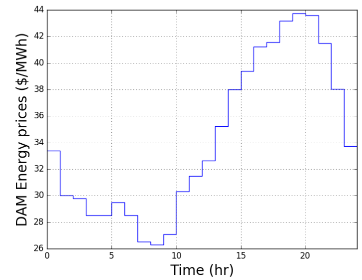
$\pi(t)$

$P(t) \leq 1 \text{ MW}$

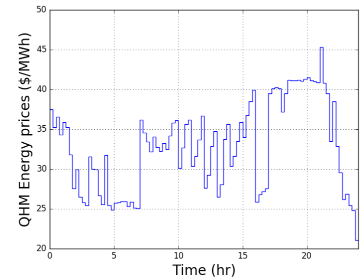
$E(t) \leq 0.5 \text{ MWh}$

Energy Prices:

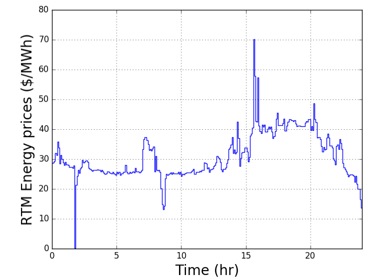
Day-ahead market
(Time scale: 1 hour)



Quarter-hourly market
(Time scale: 15 min)

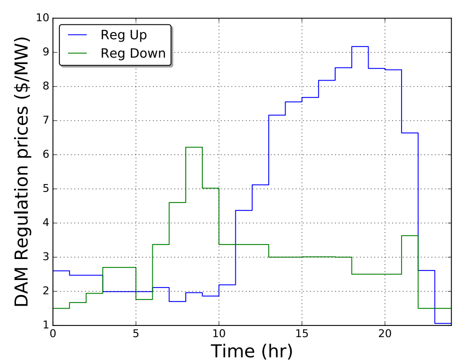


Real-time market
(Time scale: 5 min)

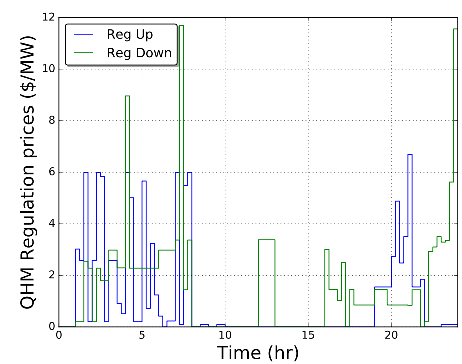


Regulation Prices:

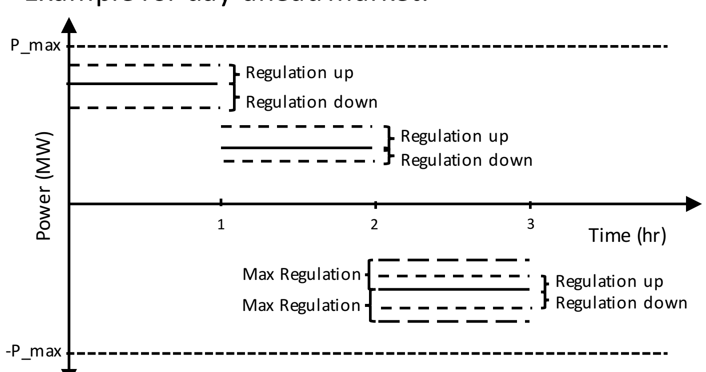
Day-ahead market
(Time scale: 1 hour)



Quarter-hourly market
(Time scale: 15 min)



Example for day-ahead market:



Optimization Model for one day: Constraints and Objective Function

$$R := \{1, .., n_r\},\ Q := \{1, .., n_q\},\ D := \{1, .., n_d\}$$

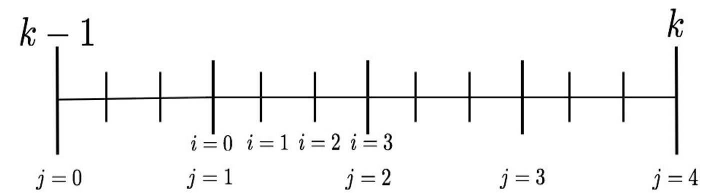
where, $n_r = 3,\ n_q = 4,\ n_d = 24$

$$i \in R,\ j \in Q,\ k \in D$$

$$\Delta t_r = 5 \text{ min},\ \Delta t_q = 15 \text{ min},\ \Delta t_d = 60 \text{ min}$$

Energy balance equations for the battery at each subinterval:

$$E_{i,j,k} = E_{i-1,j,k} - \eta(P_{i,j,k} + P_{j,k} + P_k)\Delta t_r$$
$$E_{1,j,k} = E_{n_r,j-1,k} - \eta(P_{1,j,k} + P_{j,k} + P_k)\Delta t_r$$
$$E_{1,1,k} = E_{n_r,n_q,k-1} - \eta(P_{1,1,k} + P_{1,k} + P_k)\Delta t_r$$
$$E_{1,1,1} = E_0 - \eta(P_{1,1,1} + P_{1,1} + P_1)\Delta t_r$$



Energy regulation at each subinterval:

$$P_{i,j,k} + P_{j,k} + P_k + R^U_{j,k} + R^U_k \le P_{max}$$
$$P_{j,k} + P_k + R^U_{j,k} + R^U_k \le P_{max}$$
$$P_k + R^U_k \le P_{max}$$
$$P_{i,j,k} + P_{j,k} + P_k - R^D_{j,k} - R^D_k \ge -P_{max}$$
$$P_{j,k} + P_k - R^D_{j,k} - R^D_k \ge -P_{max}$$
$$P_k + R^D_k \ge -P_{max}$$

Bounds on variables:

$$0 \le E_{i,j,k} \le E_{max}$$
$$-P_{max} \le P_{i,j,k} \le P_{max}$$
$$-P_{max} \le P_{j,k} \le P_{max}$$
$$-P_{max} \le P_k \le P_{max}$$

$$0 \le R^U_{j,k} \le R_{max}$$
$$0 \le R^U_k \le R_{max}$$
$$0 \le R^D_{j,k} \le R_{max}$$
$$0 \le R^D_k \le R_{max}$$

Revenue from energy market:

$$Rev_E = \sum_{i \in R} \sum_{j \in Q} \sum_{k \in D} \Delta t_r(\pi^E_{i,j,k} P_{i,j,k}) + \sum_{j \in Q} \sum_{k \in D} \Delta t_q(\pi^E_{j,k} P_{j,k}) + \sum_{k \in D} \Delta t_d(\pi^E_k P_k)$$

Revenue from regulation market:

$$Rev_R = \sum_{j \in Q} \sum_{k \in D} \Delta t_q(\pi^U_{j,k} R^U_{j,k}) + \sum_{k \in D} \Delta t_d(\pi^U_k R^U_k) + \sum_{j \in Q} \sum_{k \in D} \Delta t_q(\pi^D_{j,k} R^D_{j,k}) + \sum_{k \in D} \Delta t_d(\pi^D_k R^D_k)$$

Objective:

$$Max\ Rev_E + Rev_R$$

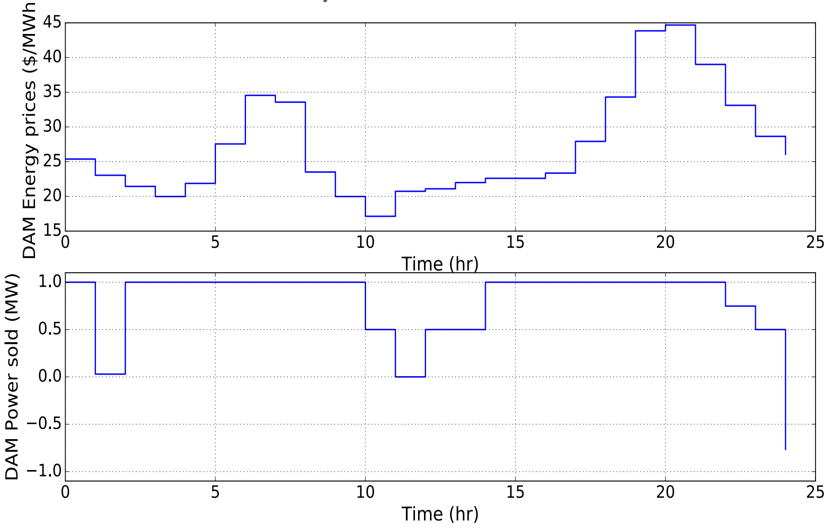
Results: Solving Complete Optimization Problem for 1 year

- Approach:
  - A single optimization problem formulated to maximize revenues of the whole year
- Problem size:
  - 911041 linear constraints
  - 1103761 variables
- Computation time (Solved in Julia using Gurobi solver)
  - **~ 20 seconds**
- Total annual revenues: **$293,125**
  - Revenues from energy sale: $201,281
  - Revenues from regulation: $91,844

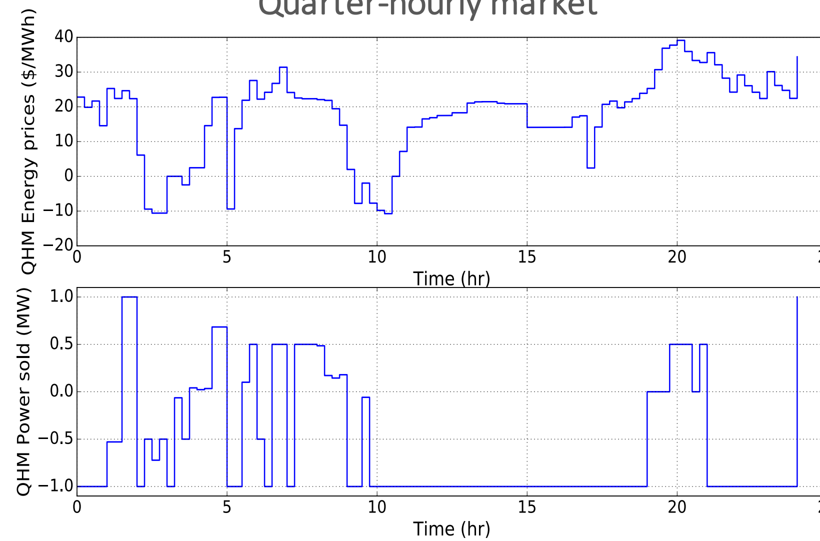
Results: Simultaneously Solving Complete Optimization Problem for 1 year

Energy trading profile in a day:

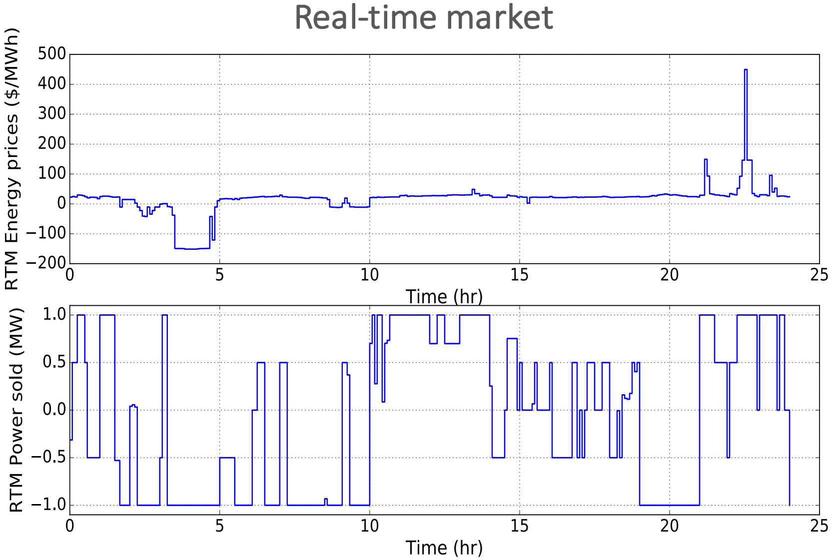
Day-ahead market



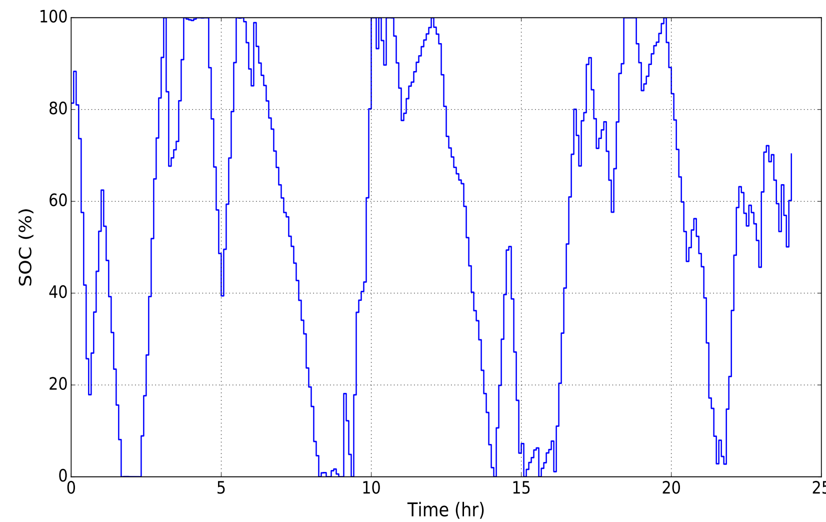
Quarter-hourly market



Real-time market



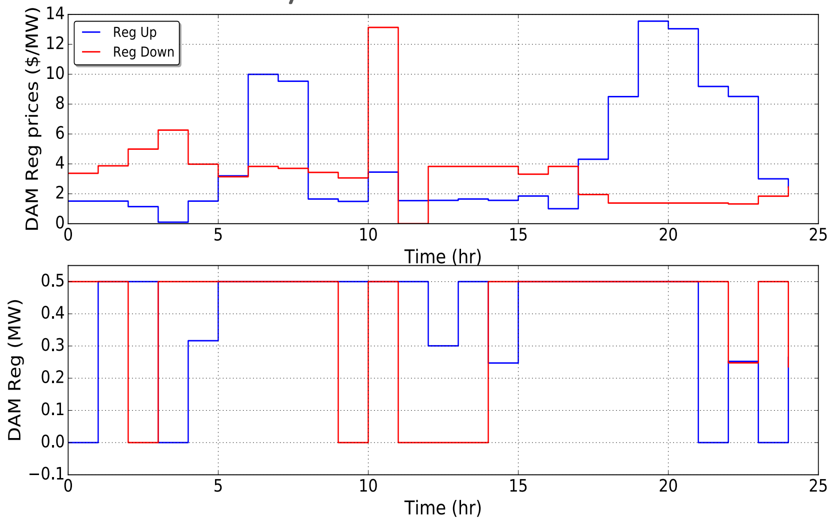
State of charge of battery



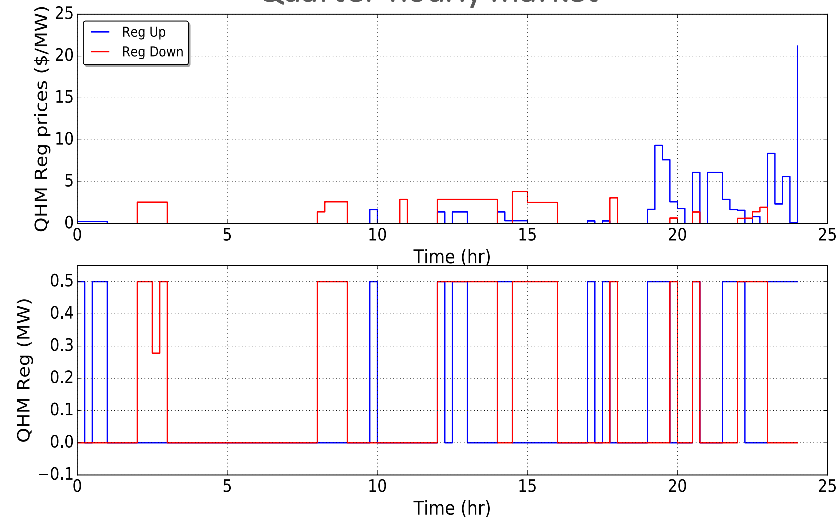
Results: Simultaneously Solving Complete Optimization Problem for 1 year

Regulation trading profile in a day:

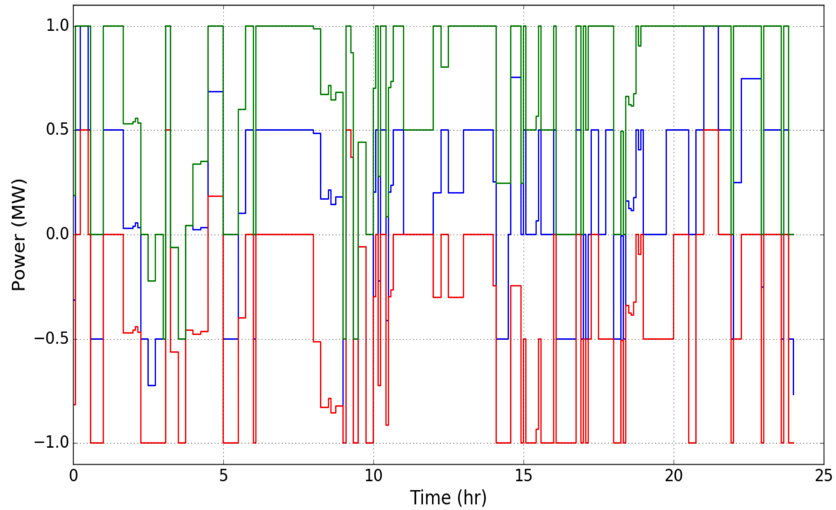
Day-ahead market



Quarter-hourly market



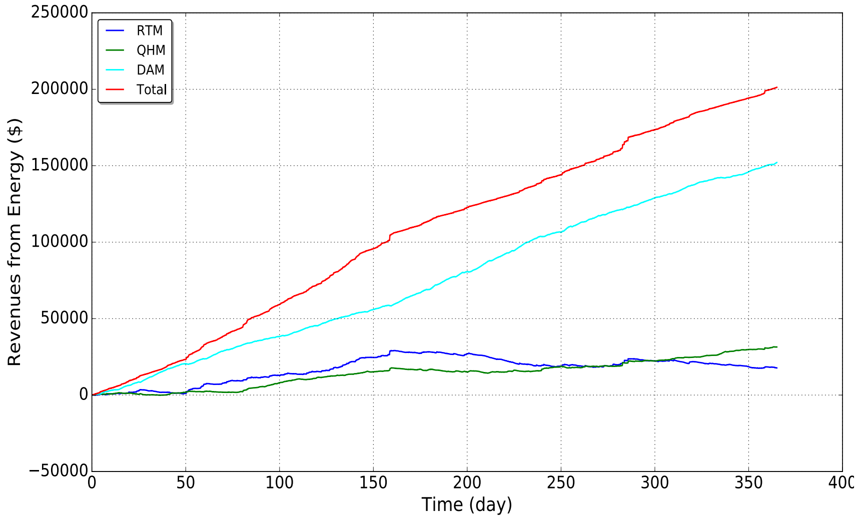
Power and regulation band



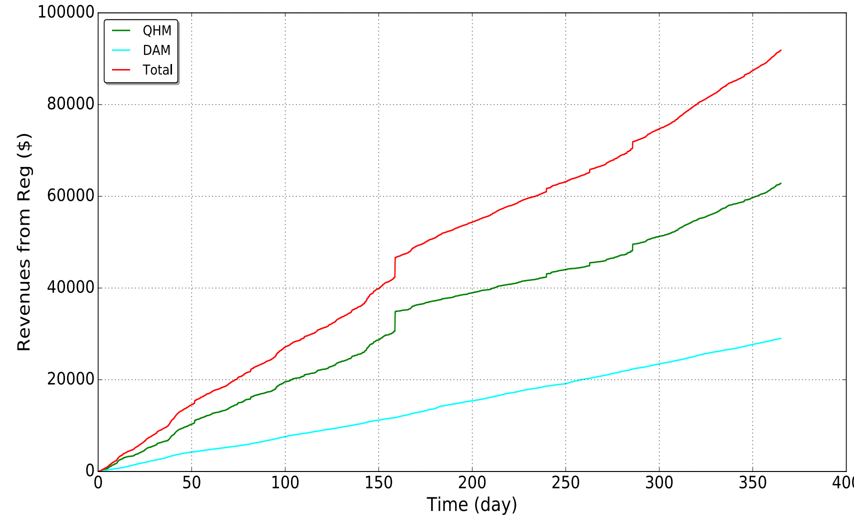
Results: Solving Complete Optimization Problem for 1 year

Cumulative revenues in a year:

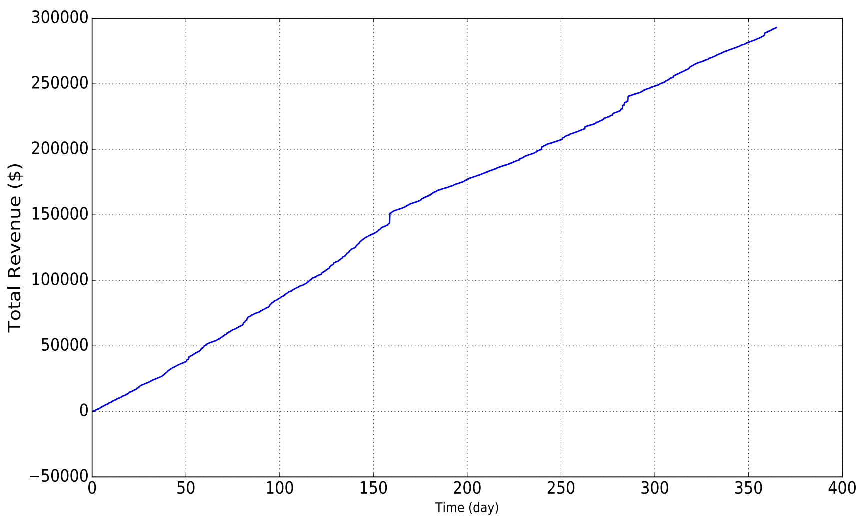
Revenues from energy sale



Revenues from regulation



Total revenues



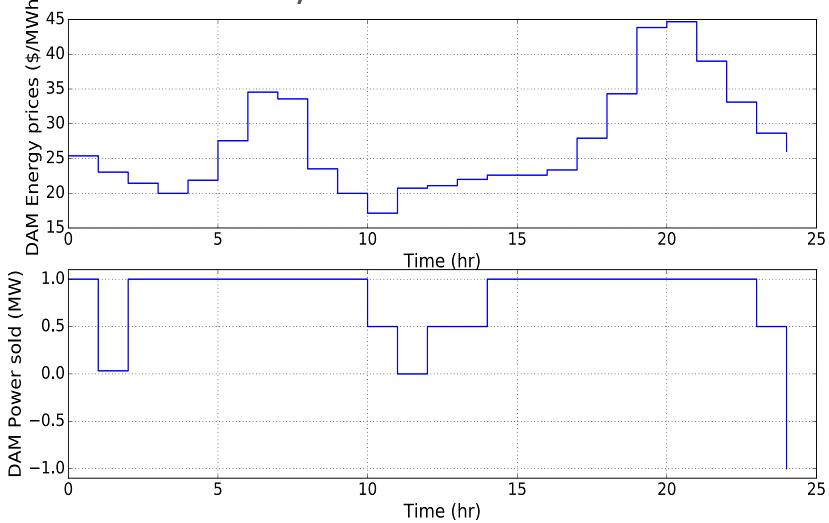
Results: Solving with Rolling Horizon of 1 Day

- Approach:
  - An optimization problem formulated to maximize revenues of each day sequentially
  - Takes the solution of the end of previous day as the initial point for the present day
- Problem size for each day:
  - 2497 linear constraints
  - 3025 variables
- Computation time (Solved in Julia using Gurobi solver)
  - 0.01-0.02 seconds for each day
  - 5-10 seconds for whole year
- Total annual revenues: **$296,985**
  - Revenues from energy sale: $205,835
  - Revenues from regulation: $91,150

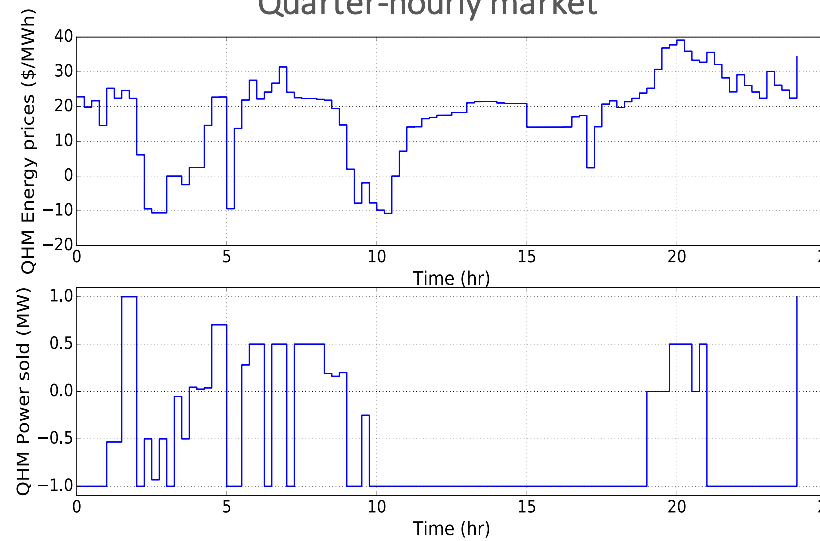
Results: Solving with Rolling Horizon of 1 Day

Energy trading profile in a day:

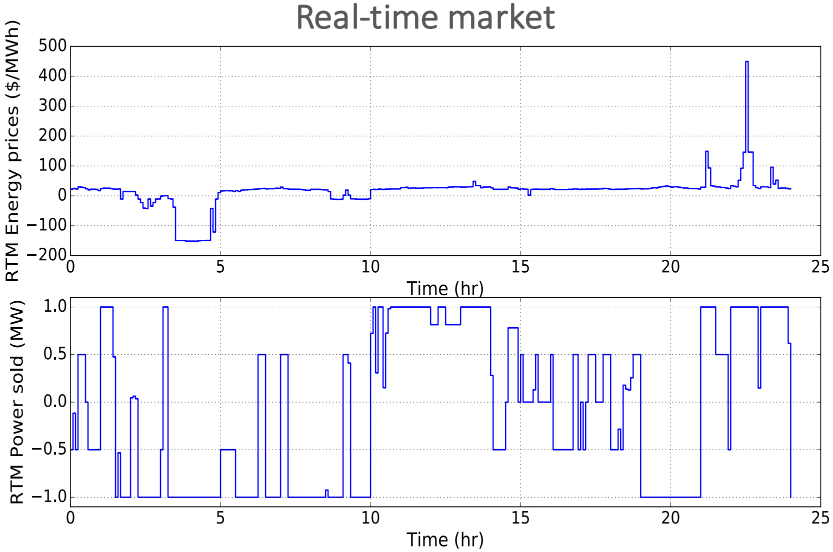
Day-ahead market



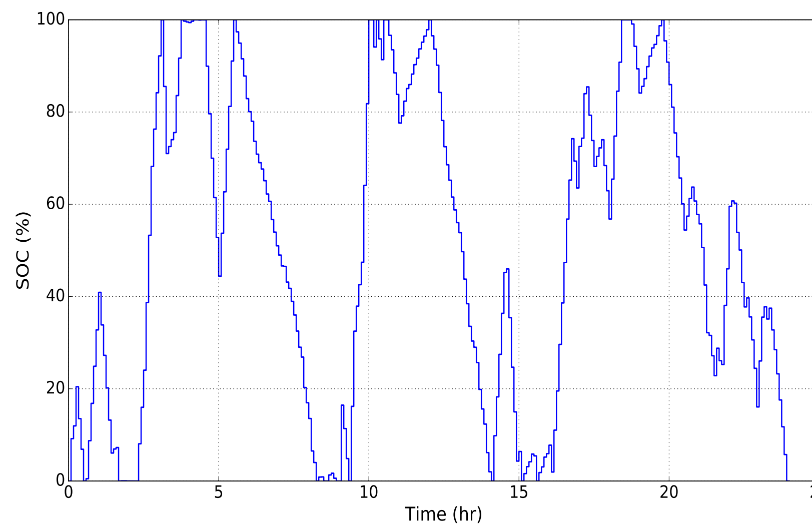
Quarter-hourly market



Real-time market



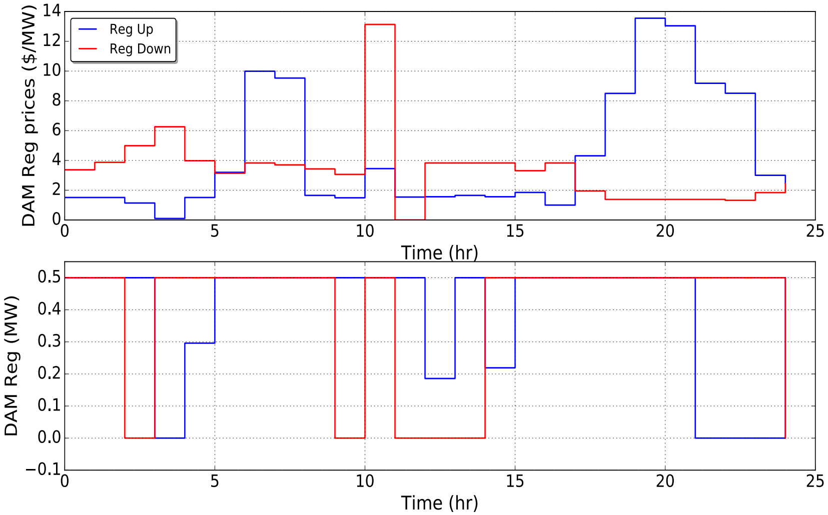
State of charge of battery



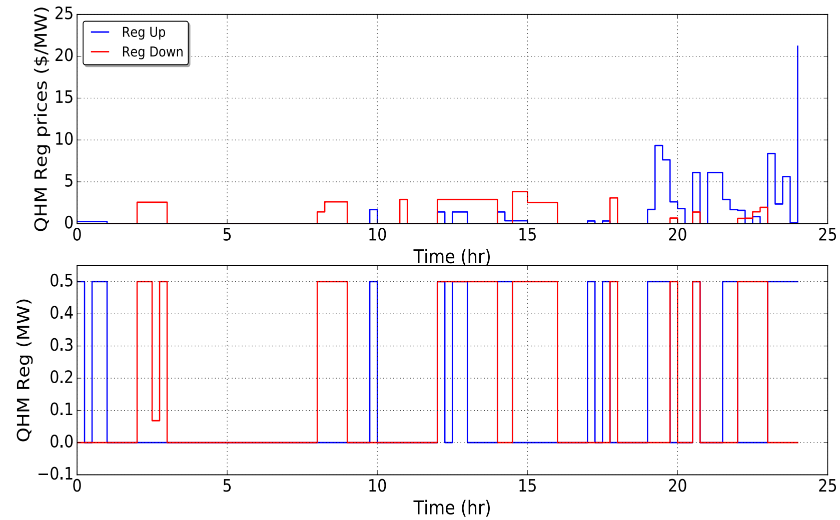
Results: Solving with Rolling Horizon of 1 Day

Regulation trading profile in a day:

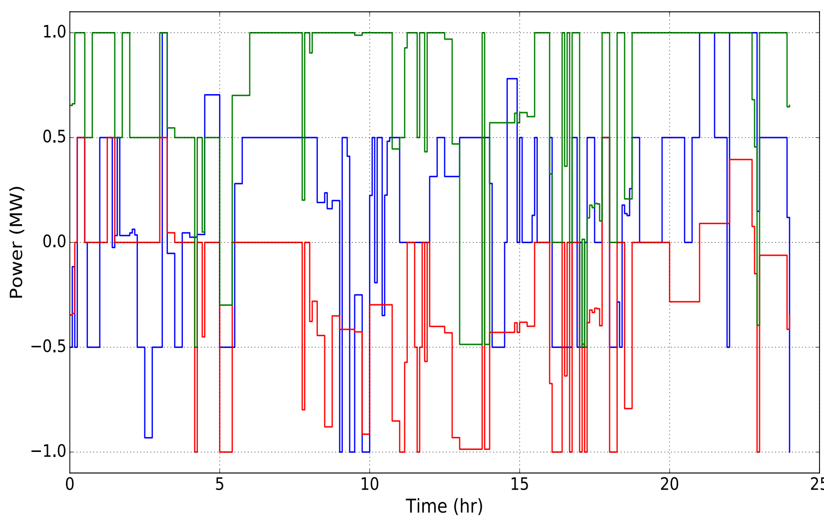
Day-ahead market



Quarter-hourly market



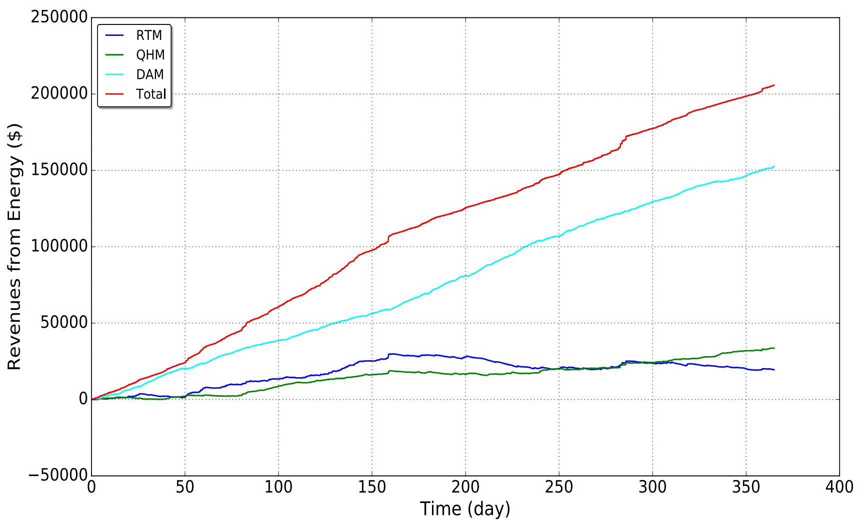
Power and regulation band



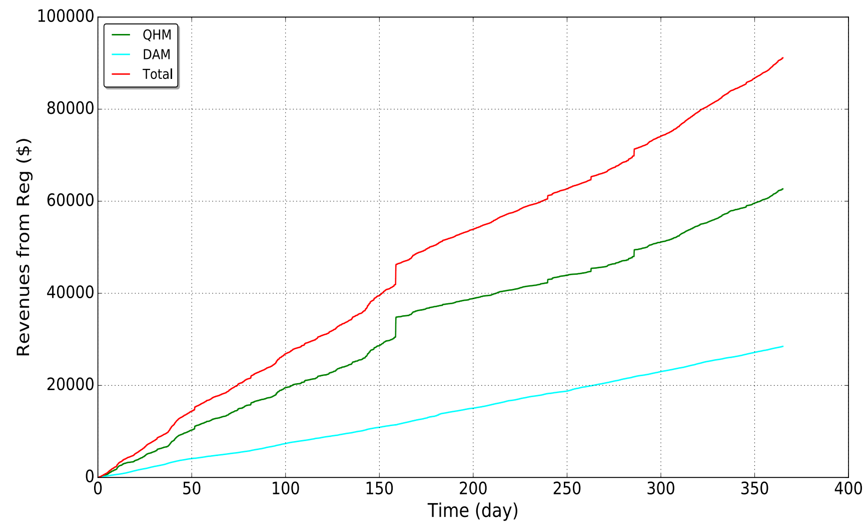
Results: Solving with Rolling Horizon of 1 Day

Cumulative revenues in a year:

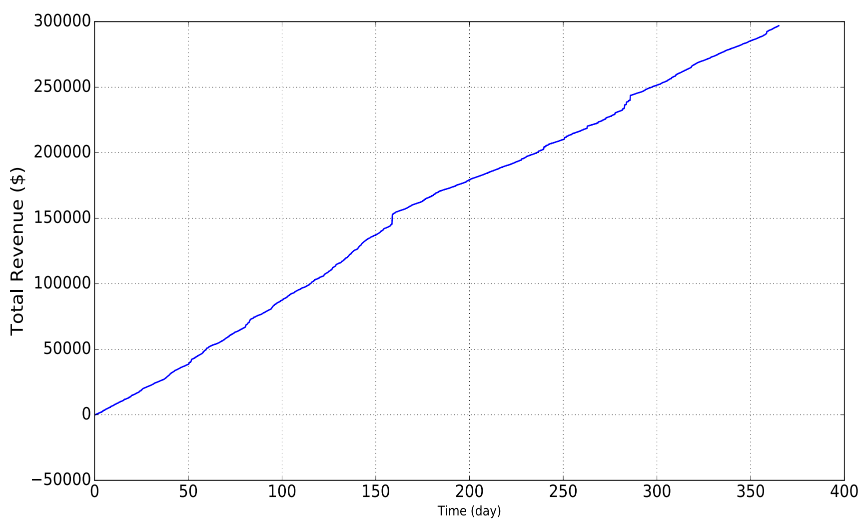
Revenues from energy sale



Revenues from regulation



Total revenues



Comparison

Simultaneously solving

- Problem size:
  - 911041 linear constraints
  - 1103761 variables
- Computation time
  - ~ 20 seconds
- Total annual revenues: **$293,125**
  - Revenues from energy sale: $201,281
  - Revenues from regulation: $91,844

Rolling horizon

- Problem size for each day:
  - 2497 linear constraints
  - 3025 variables
- Computation time
  - 0.01-0.02 seconds for each day
  - ~ 5-10 seconds for whole year
- Total annual revenues: **$296,985**
  - Revenues from energy sale: $205,835
  - Revenues from regulation: $91,150

Conclusions

- Rolling horizon approach is much computationally faster than the simultaneous approach
- Although trends of the solutions are similar, rolling horizon approach results in slightly higher annual revenues than the simultaneous approach
- Expect the rolling horizon approach to perform much better than the simultaneous approach to solve stochastic model for this problem
- A real-time optimal controller can be designed to operate the battery in an optimal way with rolling horizon approach

Thank you!