Economic Nonlinear Model Predictive Control for the Optimization of Gas Pipeline Networks

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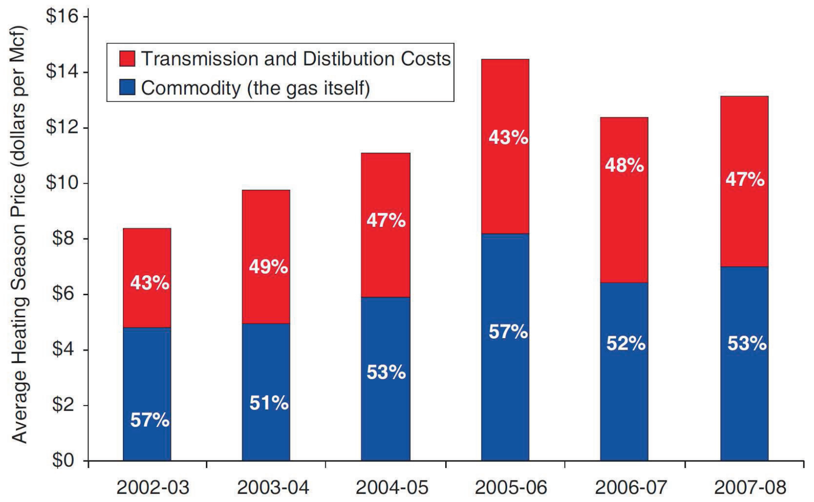
Natural Gas Industry

- Globally increasing demand & production of natural gas.
- Demand distribution (as of 2008) 21 % residential, 13 % Commercial, 34 % Industrial, 29 % Electric power generation.
- Wide scope for optimization [1]
  - Production - Well placement to maximize recovery, production scheduling.
  - Transportation - Network design, compressor location, fuel usage minimization
  - Market - Regulated, Deregulated markets
- Applying Economic Model Predictive Control to gas transportation.



Mcf = Thousand cubic feet.
Source: History: Energy Information Administration, *Natural Gas Monthly*, September 2007.
Projections: Energy Information Administration, *Short Term Energy Outlook* (November 2007).

[1] Zheng et al., *Optimization models in the natural gas industry*, Energy Systems, 1:121-148, 2010

Gas Transmission

Trunk / Grid Transmission Pipelines:

Interconnected pipeline network of suppliers, consumers, and compressor stations.

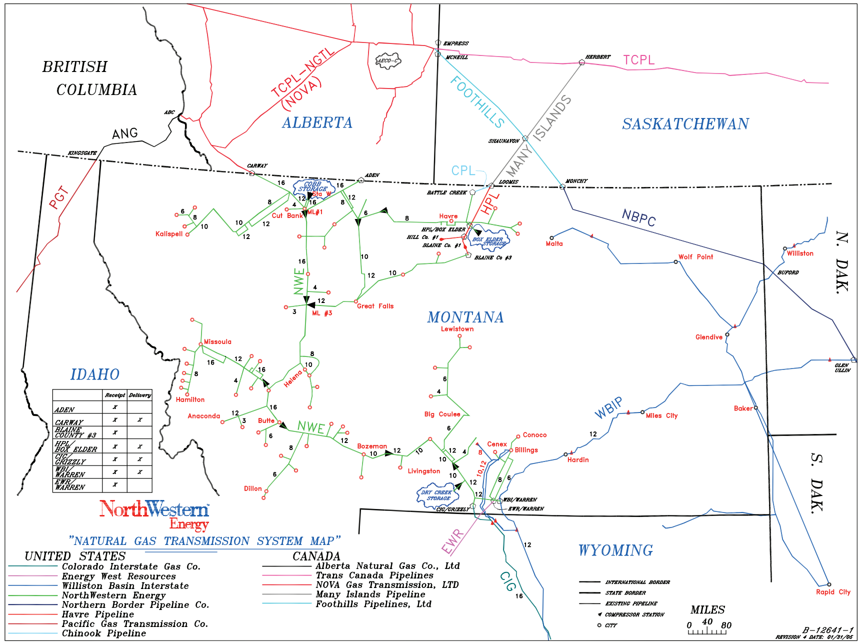
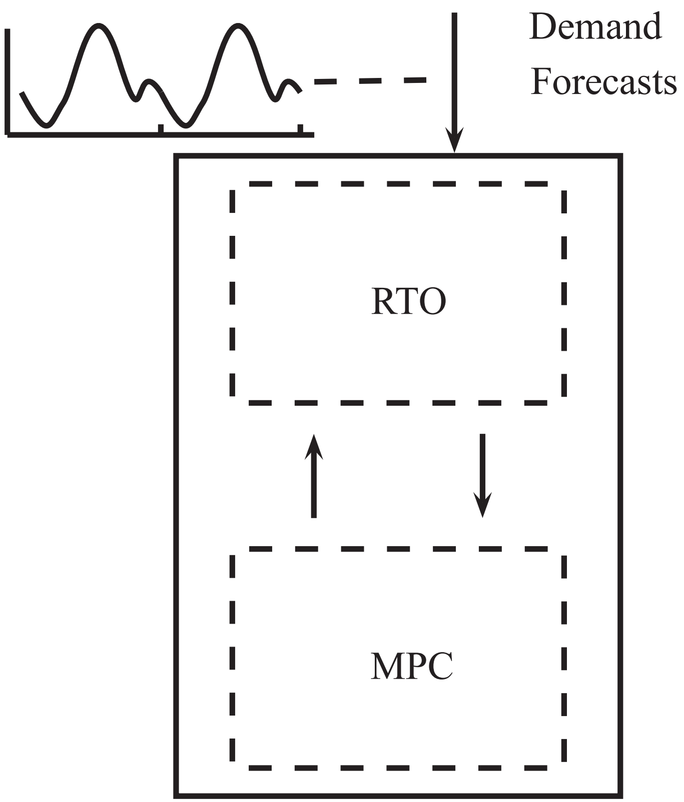


Figure: Schematic of a grid pipeline network

- **Supply**: Manipulate flow of gas into the network.
- **Consumers**: Contracts with gas company. Flow demands must be satisfied at or above a contract pressure.
- **Compressor Stations**: Compression of gas every 50-100 mi, to compensate for frictional losses.
- Optimization: Meeting demands of consumers, respecting contracts, physical constraints while minimizing compression costs.

Economic MPC



Dynamic RTO

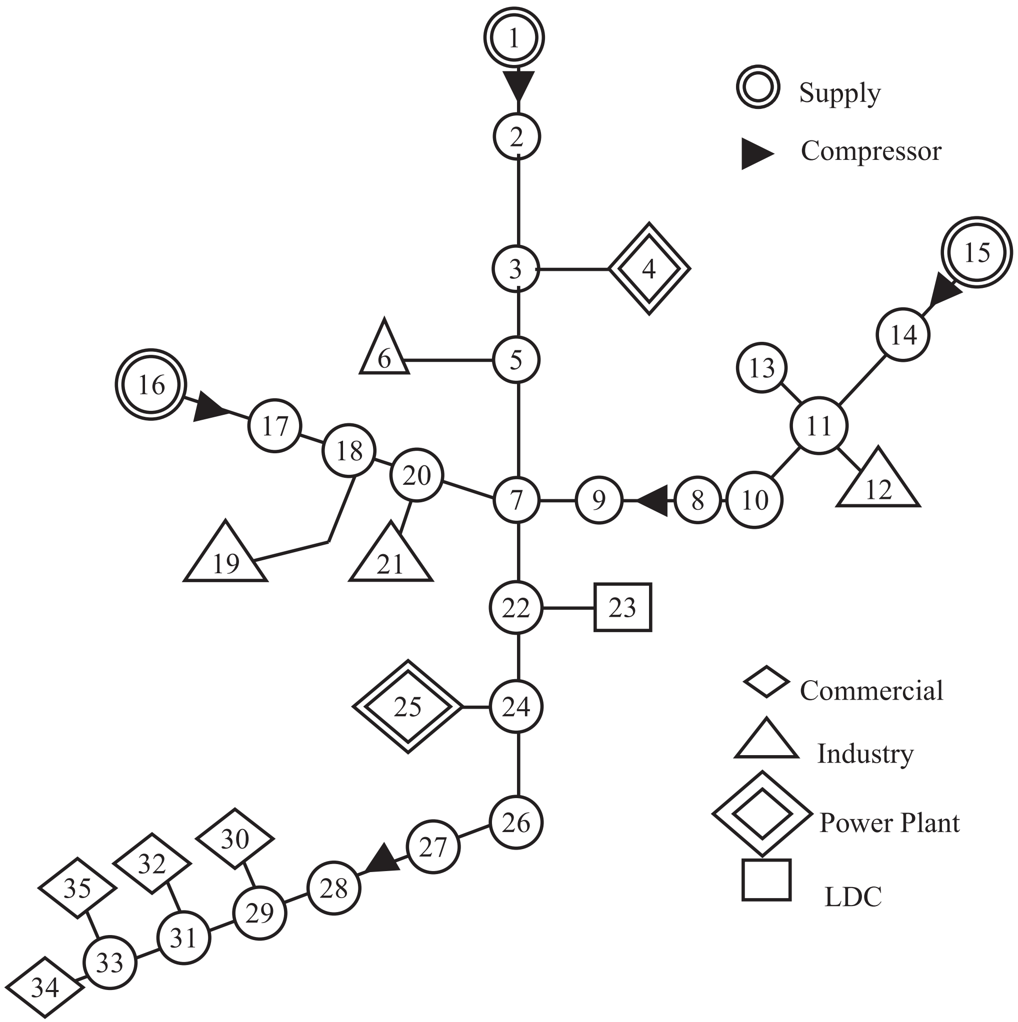
DRTO:

$$\begin{aligned} \min_{Power_j(t)} \quad & \sum_{j \in CA} \int_0^{T_f} Power_j(t) \\ \text{s.t.} \quad & \dot{x} = f(x,u), \\ & g(x,u) \leq 0, \\ & x_{T_f} \in \mathcal{X}. \quad \text{(Terminal Constraint)} \end{aligned}$$

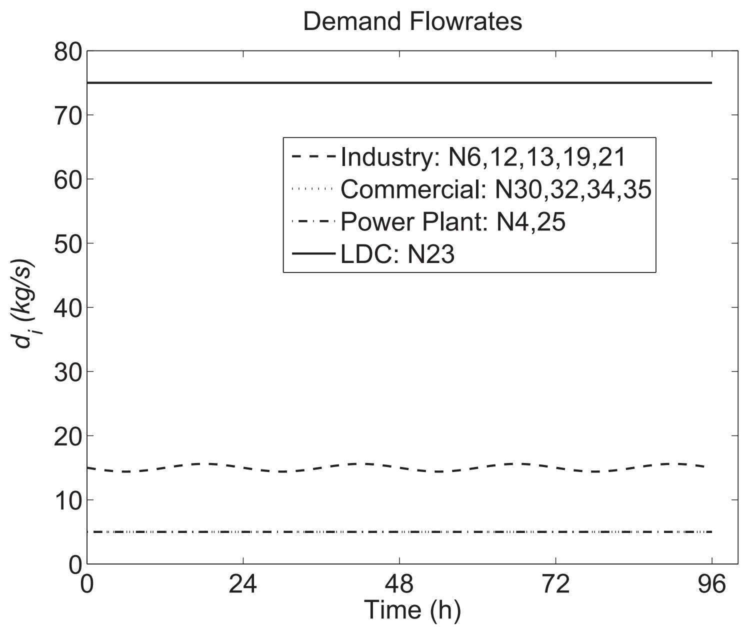
- Using an economic objective as the stage cost for MPC, directly optimizes the transients [a]

[a] Optimizing Process Economic Performance Using Model Predictive Control J. B. Rawlings, R. *Lecture Notes in Control and Information Sciences*, 384:119-138, 2009

Large Network Topology



- 3 Suppliers, 12 Demand nodes, 5 Compressors
- Sinusoidal demands ∼ Approximation to real demand.



- $P_{contract} = 500$ kPa
- $N = 3$ days, $K = 1$ day, $h = 1$ hr
- NLP size: 109057 Vars, 95099 Eqns

Simulations: Nominal Case

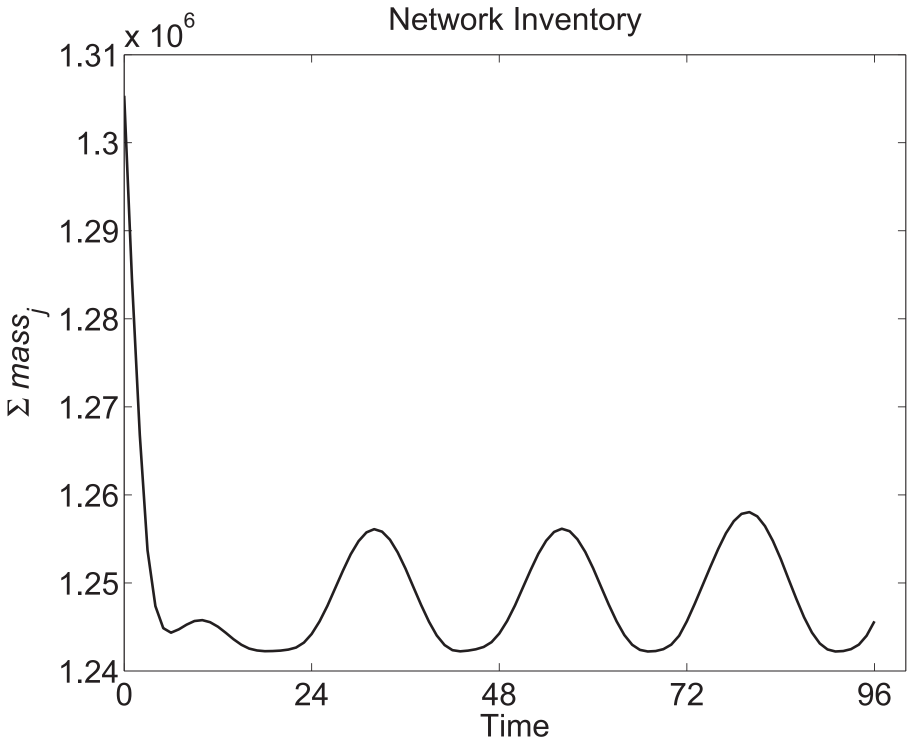


Figure: Network Inventory

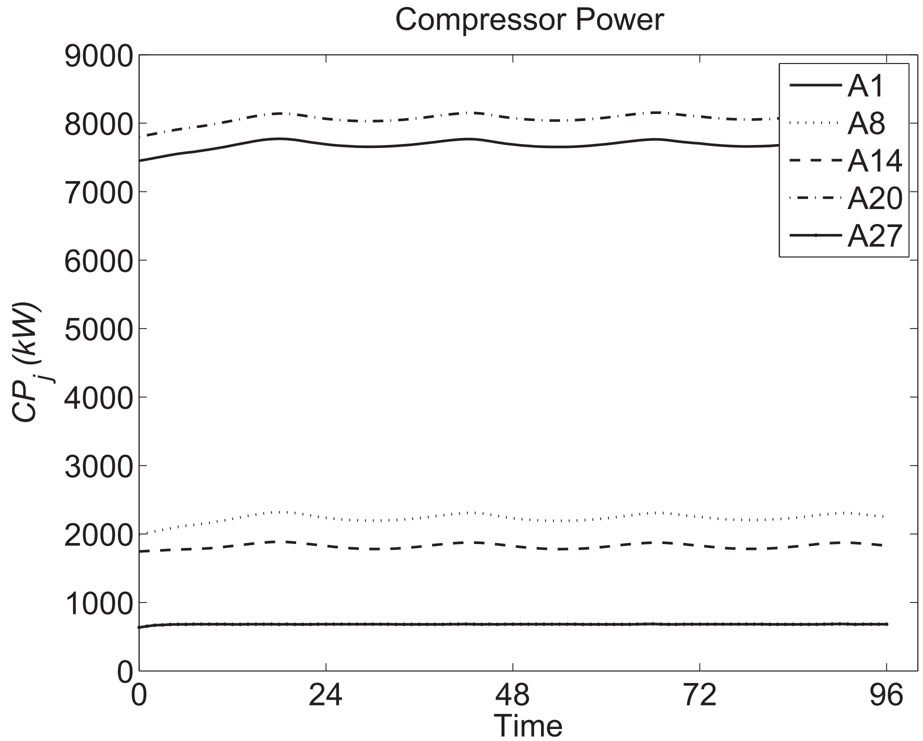
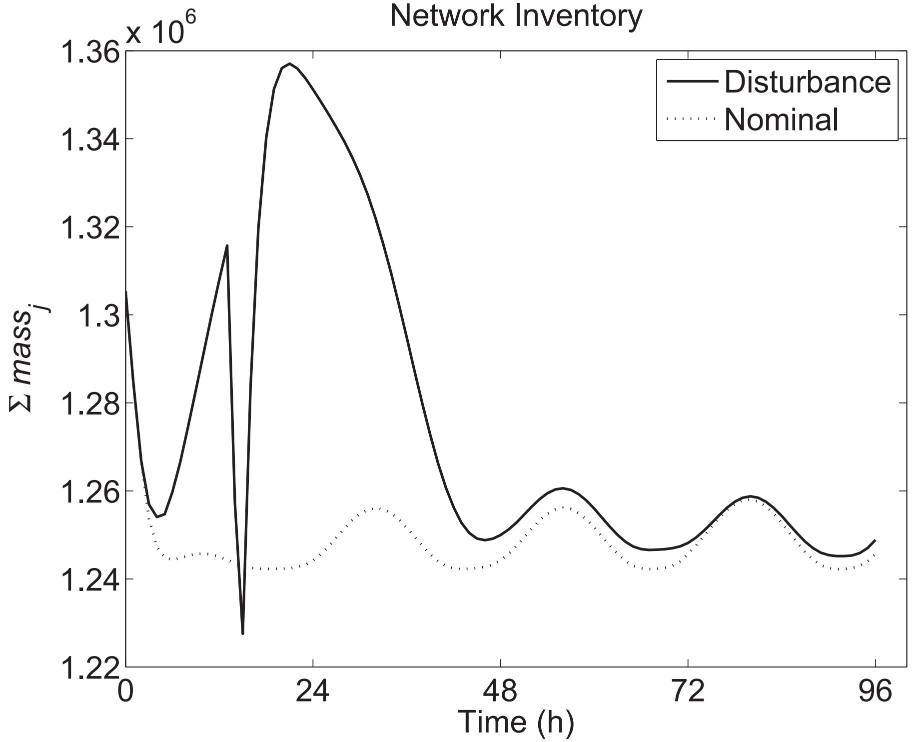


Figure: Compressor Profiles

Simulations: Disturbance Handling



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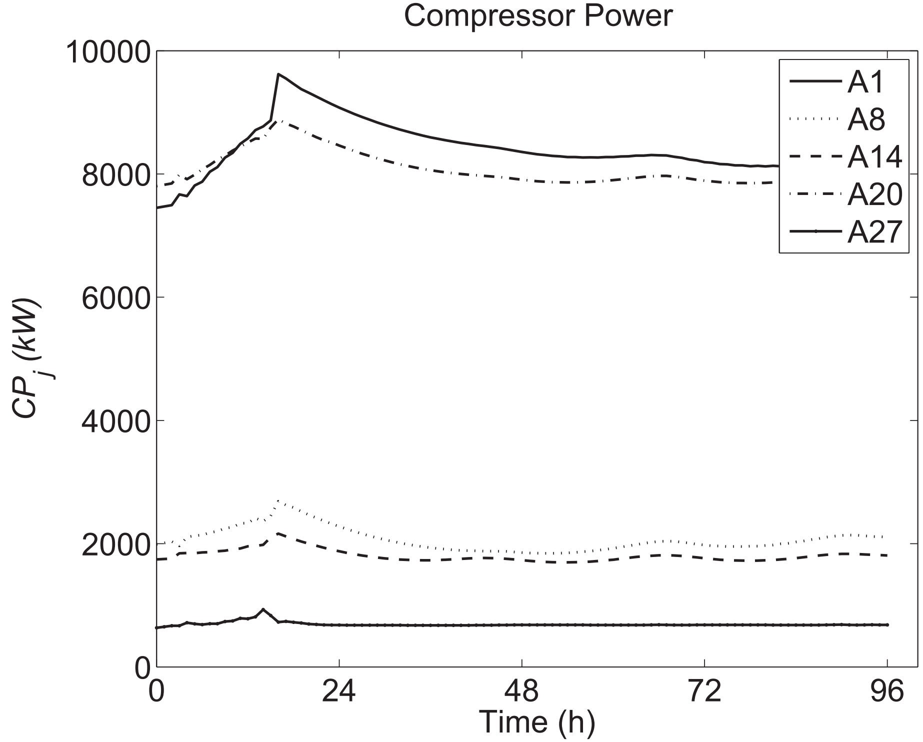
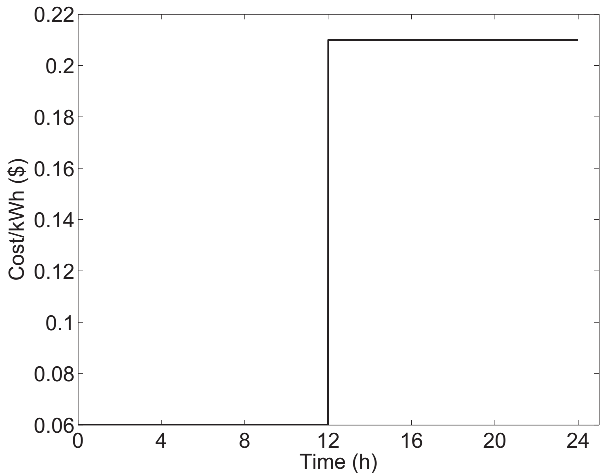


Figure: Compressor Profiles

Electricity Pricing

- Compressors can run either by [7]
  - Combustion of a part of the natural gas or,
  - Electric power (Environmental and safety reasons)
- Complex electricity pricing schemes: Electricity prices vary through the day and consumers are encouraged to use more when power is cheaper.
  - *Time of day pricing*: Two 12-h time periods (on-peak and off-peak)
- Objective function modified to include cost of energy:

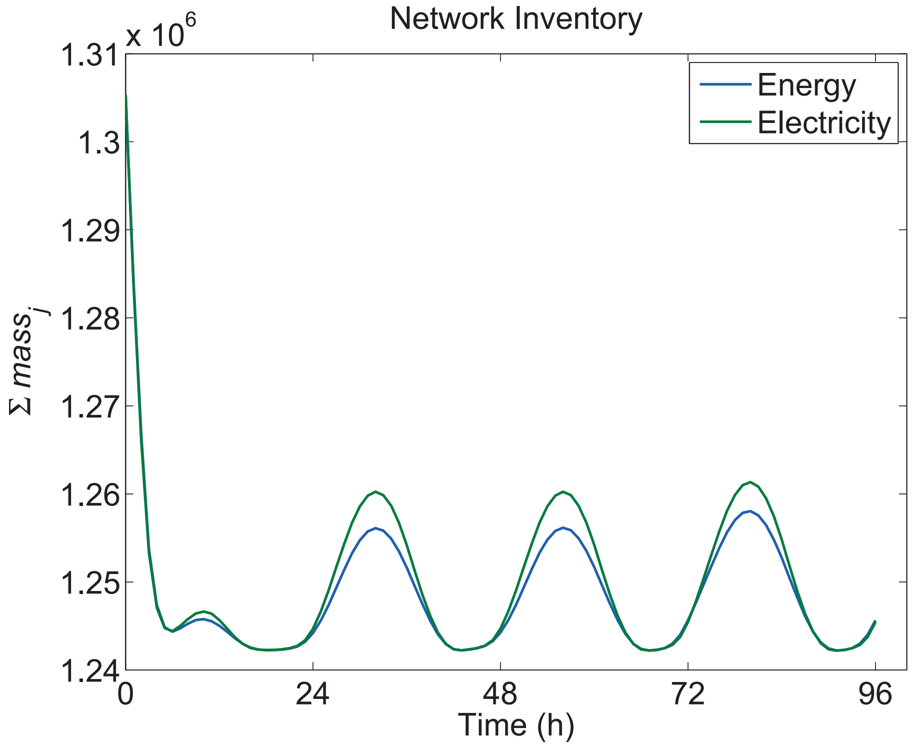
$$\underbrace{\sum_{j \in CA} \int_{t}^{t+N+K} Power_j \mathbf{Cost_t} dt}_{\text{Total Energy Cost}} + \underbrace{\rho \sum_{j \in CA} \sum_{t \in T} (Power_j(t+1) - Power_j(t))^2}_{\text{Smoothing term}} + \underbrace{c_d \max_t \sum_j Power_j(t)}_{DemandCharge}$$



- Time of day pricing data (SRP Utility)

[7] Energy Information Administration, Office of Oil and Gas, November 2007

Simulations: Electricity Pricing



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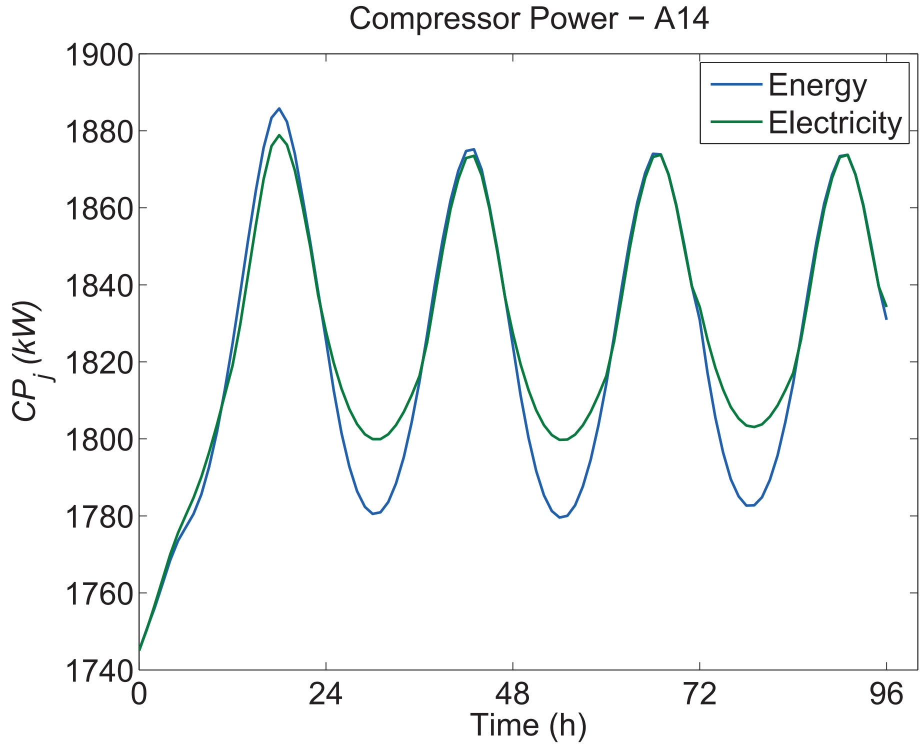

Figure: Compressor Profiles

Cost savings of 0.3 % percent over the horizon.