PhD Proposal

Approaches to Enable Demand Response by Industrial Loads for Regulation, Reserve and Load Following Provision

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Electrical & Computer ENGINEERING

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Why Demand Response ?

- Sustainable energy future and a green planet
  - renewable generation
  - need more balancing power
- Power balance
  - generation equals demand
  - traditional balancing power: generators
- Demand response
  - adjust the other side of the equation
  - potentially provides a cost-effective solution

Why Industrial Loads ?

- Demand response resources
  - residential, commercial, industrial loads
    - e.g. residential areas, electric vehicles, buildings, data centers, pumps, furnaces, fans, ...
- Industrial loads
  - advantages
    - infrastructure
      - already installed
    - response
      - large, fast, accurate
    - economic incentive
      - strong
  - challenges
    - reliability
      - critical safety constraint
    - complexity
      - production activities
    - granularity
      - power change response

Thesis Goal

- Solution to Challenges for industrial loads
  - reliability
    - aluminum smelting, Chloralkali process, electrolysis process, ...
  - complexity
    - steel manufacturing, air separating, ...
  - granularity
    - cement crushing, thermal-mechanical pulping, ...

- Particular focus on ancillary services

Problem Statement

I. Account for uncertainty
   – how to optimally participate in the uncertain markets, ensuring that the critical reliability constraints are satisfied?

II. Handle complexity of process
   – how to model and solve the complex industrial DR problems within acceptable computation time?

III. Overcome granularity restrictions
   – how to integrate the industrial loads with poor granularity to fully exploit their DR potentials?

Outline and Proposed Approach

- Introduction of Electricity Markets
- Account for Uncertainty
  - Optimize Regulation Capacity
  - Optimal Bidding of Energy and Reserve
- Handle Complexity of Process
  - Modeling Controllable Transformers
  - Modeling Spinning Reserve Provision
  - Tailored Branch and Bound Algorithm
- Overcome Granularity Restriction
  - MPC Coordination of Loads and Storage

Electricity Markets

- Energy market: electricity as a commodity
  - values depend on time $\neq$ a barrel of oil
    - – expensive to store electricity in large quantities
    - – produce, consume: at the same time!
- Ancillary service market
  - – ensure supply security: generation = consumption
  - – handle uncertainties, e.g. renewable generation
    - spinning reserve: generator or transmission outage
    - regulation, load following: load fluctuations
  - – traditionally by generators
    - e.g. compulsory provision requirement for generators

Electricity Markets

- Comparison

Service	Response Speed	Response Direction	Frequency, Duration	Market Cycle
Regulation	seconds	up, down	continuous	hourly
Spinning reserve	< 10 min	down	rarely dispatched, 10 min to 120 min	hourly

- Prices in MISO [1]
  - energy ~ $30/MWh
  - regulation ~ $10/MW (capacity + mileage)
  - spinning reserve ~ $1/MW (capacity + dispatch)

[1] MISO: Midcontinent Independent System Operator. Prices available: https://www.misoenergy.org/MarketsOperations/RealTimeMarketData/Pages/AncillaryMarketMCP.aspx

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Aluminum Smelting

- Aluminum
  - the most widely used nonferrous metal
- Smelting: electrolytic process
  - consumes large amounts of electric energy
    - ~ 7kWh electricity per pound (~12kWh, 50 years ago)
  - only commercial way to produce aluminum
  - cells (pots) connected as potline
  - chemical reaction
    - $2Al_2O_3 + 3C \Rightarrow 4Al + 3CO_2$
    - alumina (ore) to aluminum

Fig 1. Aluminum applications.

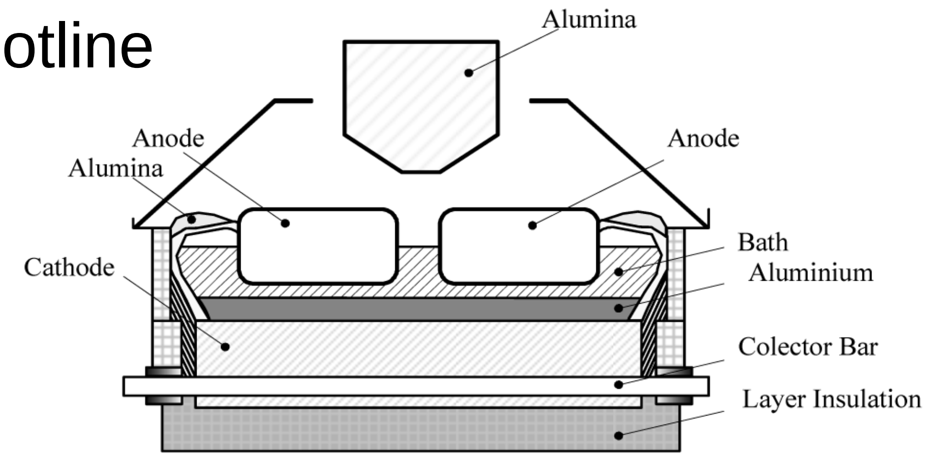


Fig 2. Aluminum smelting cell [1]

[1] 2011, Modeling Aluminum Smelter Plants Using Sliced Inverse Regression With a View Towards Load Flexibility.

Power Consumption of Smelter

- DC power, by rectifier [1]
  - plant power magnitude: hundreds of MWs
    - each cell: voltage ~4V, current 150~250 kA, power 0.6~1MW
    - each potline: dozens of cells, tens of MWs of power
  - power change: precise and fast (within seconds)
    - turn up/down potline input voltage
      - rectifier tap changer, 0.7-1.2 MW/step
    - turn off the entire potline
      - recovery time, rotation among potlines
- Industrial DR experiences
  - Alcoa's Warrick, *DRR-Type-2* resource, MISO, US [1]
  - Trimet Aluminium, molten battery, Germany [2]

[1] 2009, Providing Reliability Services through Demand Response A Preliminary Evaluation of the Demand Response Capabilities of Alcoa Inc.
[2] http://www.businessweek.com/articles/2014-11-26/germanys-trimet-aluminium-turns-smelting-tanks-into-batteries

Optimize Regulation Capacity [1]

- Problem statement
  - decide regulation capacity under uncertainties
  - stochastic programming
    - AGC (regulation command) traces as scenarios
    - assume hourly prices known
- Optimization model
  - minimize
    - net cost
      - energy, production
      - regulation capacity, mileage
      - penalty on mismatch
      - cost on tap movement
  - subject to
    - cell temperature range
      - energy consumption for every successive hours
    - plant production amount range
    - tap movement physical limit

[1] X. Zhang and G. Hug, “Optimal regulation provision by aluminum smelters,” in IEEE Power and Energy Society General Meeting, 2014.

Optimize Regulation Capacity

- Simulation results
  - regulation capacity changes according to prices
  - increasing penalty leads to smaller mismatch

hour 1,3: higher regulation price

hour 2: lower regulation price

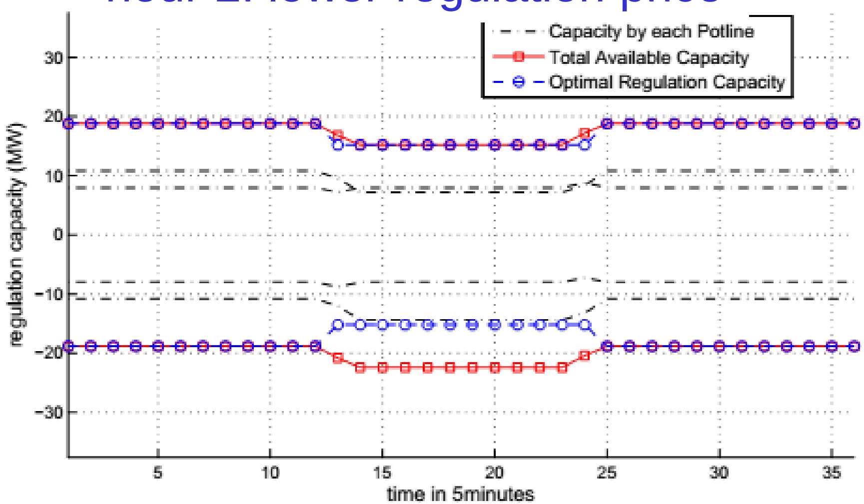


Fig 1. Regulation capacity for 3 hour simulation.

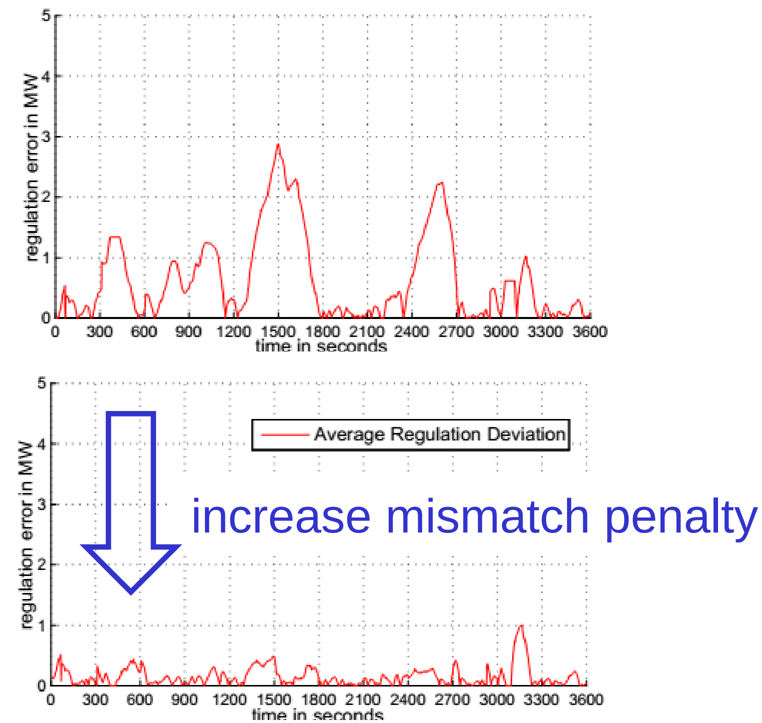


Fig 2. Changing penalties on mismatch

Optimal Bidding of Reserve and Energy [1]

- Optimally sell energy and spinning reserve
  - energy
    - long-term contract, specified power amount at fixed price
    - sell energy back in real-time market at real-time price
  - spinning reserve
    - power consumption adjustable: rectifier, shut down
  - stochastic optimization
    - price uncertainty
      - pointwise price prediction is not accurate enough
      - based on a set of (possible) price scenarios
    - maximize the expected profit over all scenarios
    - hedge the risk from prediction uncertainty

[1] X. Zhang and G. Hug, "Bidding strategy in energy and spinning reserve markets for aluminum smelters' demand response," in IEEE Innovative Smart Grid Technologies Conference, 2015

Optimal Bidding of Reserve and Energy

- Bidding strategy
  - market rule [1]
    - energy: submit a price curve
    - spinning reserve: only one Price/MW pair
  - price taker assumption
  - strategy
    - energy
      - obtain optimal $E_{s,h}$ for every scenario
      - connect the optimal MW/Price pairs
    - spinning reserve
      - seldom dispatched (~ 0.44% annual dispatch rate)
        - » simply standing by makes impressive profits
      - ask for low price, ensure clearing the optimal capacity

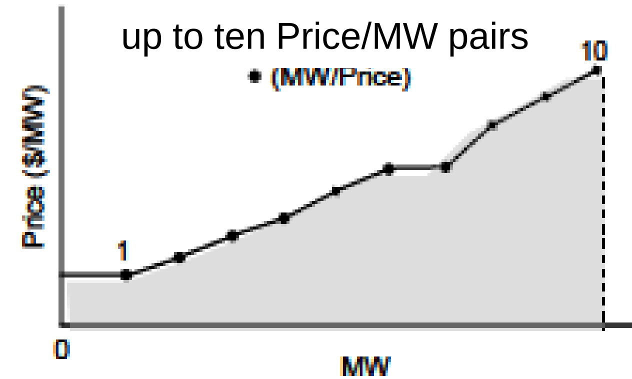


Fig 1. Energy offer curve [1]

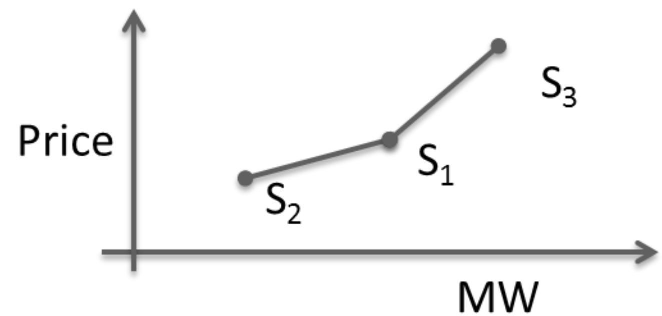


Fig 2. Optimal Price/MW pairs in hour h.

[1] Business Practices Manual: Demand Response, Feb 2013.

Optimal Bidding of Reserve and Energy

- Stochastic optimization
  - maximize
    - electricity market revenue
    - production profit
  - subject to
    - production efficiency
      - changes with loading level
    - minimum energy consumption
      - cell temperature
    - obey bidding rule
      - monotonous MW/Price pairs
    - daily production amount range

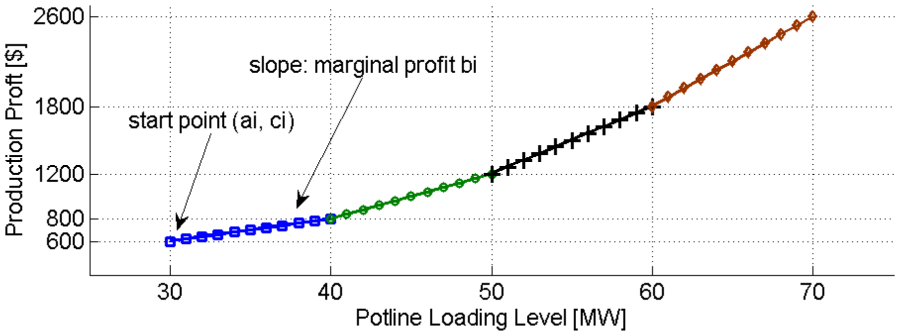


Fig. Piece-wise linear modeling of production profit.

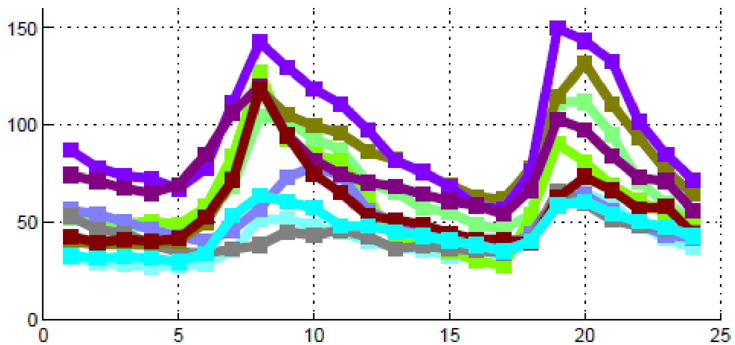
$$P_{l,s,h} = \sum_{i=1}^{n_l} (a_{l,i} N_{l,s,h,i} + \Delta P_{l,s,h,i}) \quad \forall l, s, h$$

$$0 \leq \Delta P_{l,s,h,i} \leq (a_{l,i+1} - a_{l,i}) N_{l,s,h,i} \quad \forall l, s, h, i$$

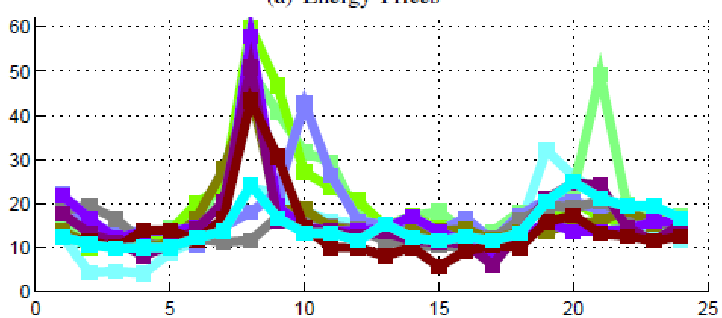
$$\sum_{i=1}^{n_l} N_{l,s,h,i} = 1 \quad \forall l, s, h$$

Optimal Bidding of Reserve and Energy

- Simulation results

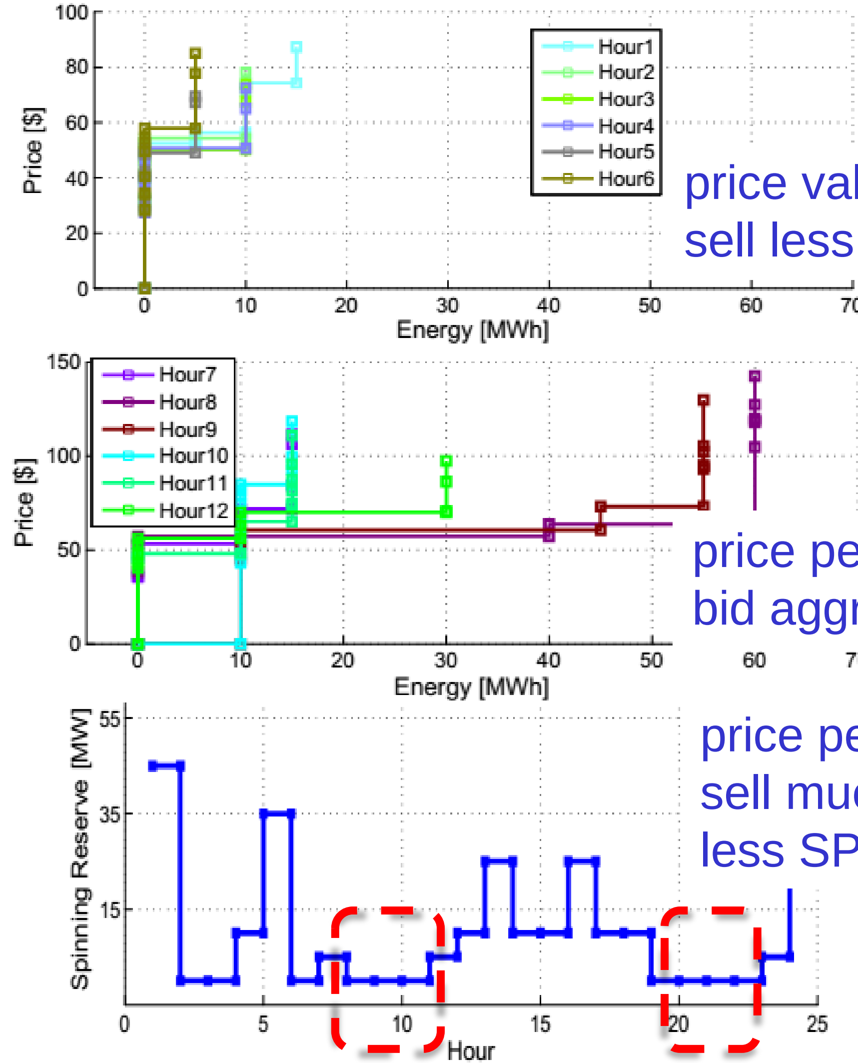


(a) Energy Prices



(b) Spinning Reserve Prices

Fig 1. Price scenarios.



price valley hours: sell less energy

price peak hours: bid aggressively

price peaks: sell much energy less SP available

Fig 2. Optimal bidding curves.

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Account for Uncertainty

- Timeline
  - 13.07-13.12, Optimize Regulation Capacity
  - 14.01-14.06, Optimal Bidding of Energy and Reserve

  - 15.07-15.12, Optimal Bidding of Energy and Regulation
    - design the bidding strategy in the energy and regulation markets
  - 16.01-16.06, Regulation by MPC with AGC Prediction
    - design real-time controller for smelter to provide regulation

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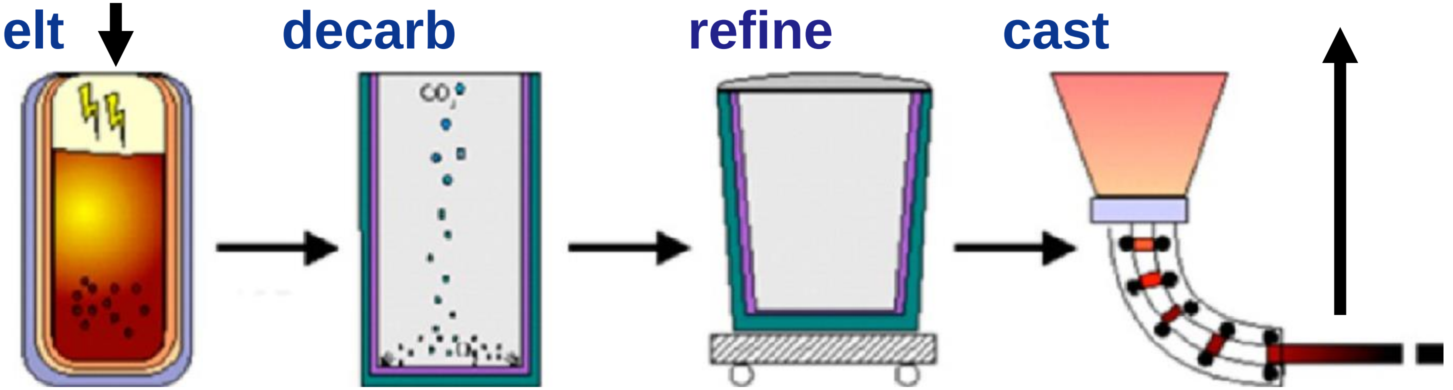
Steel Manufacturing

raw material
(e.g. metal scrap)

final products : slabs

melt **decarb** **refine** **cast**



EAF
Electric Arc Furnace

AOD
Argon Oxygen Decarbonation

LF
Ladel Furnace

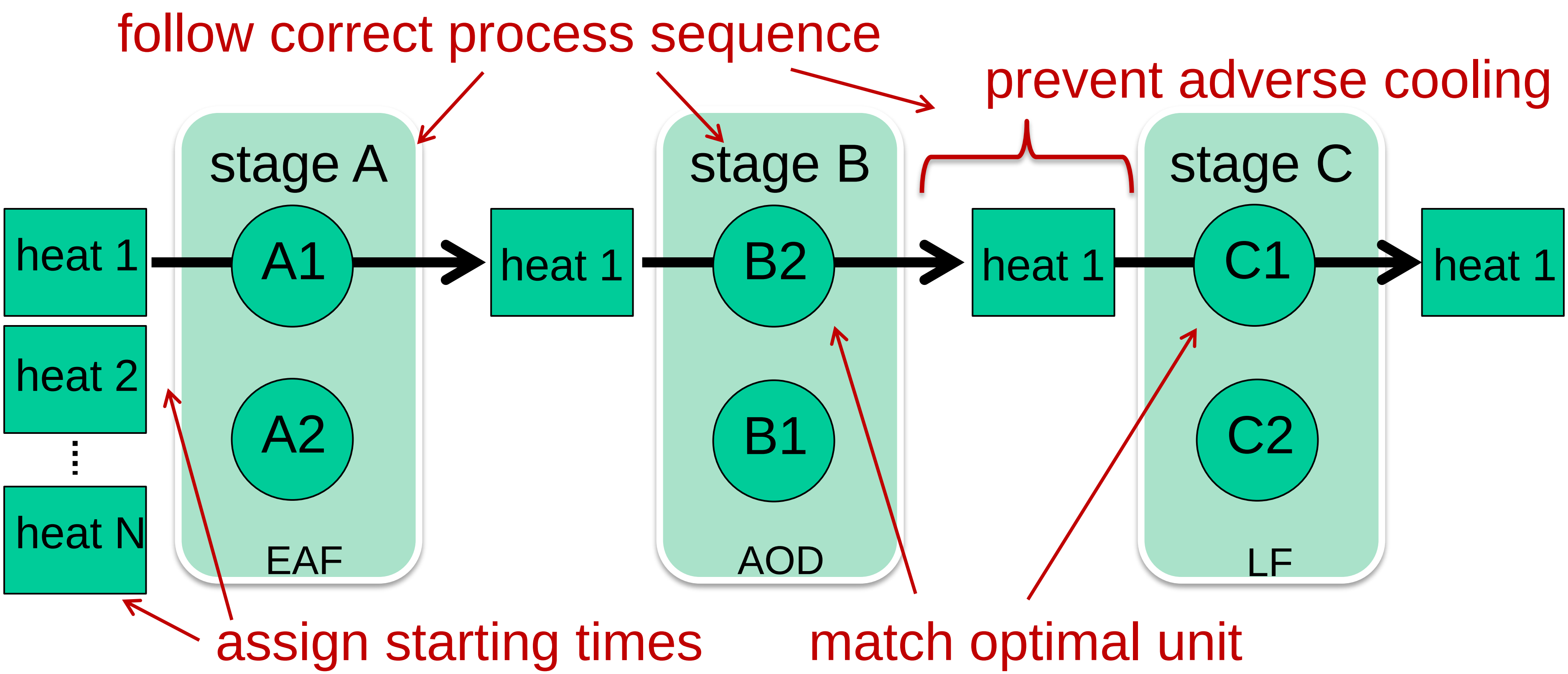
CC
Continuous Caster

Heat : a certain amount of metal

Source: P. M. Castro, L. Sun, and I. Harjunkoski, "Resource task network formulations for industrial demand side management of a steel plant,"Industrial & Engineering Chemistry Research, vol. 52, no. 36, pp.13 046–13 058, 2013.

Steel Plant Scheduling

is a complicated process !



Challenges: multi-stage, large-scale, parallel units, waiting time, …

Resource-Task Network for Steel Plants

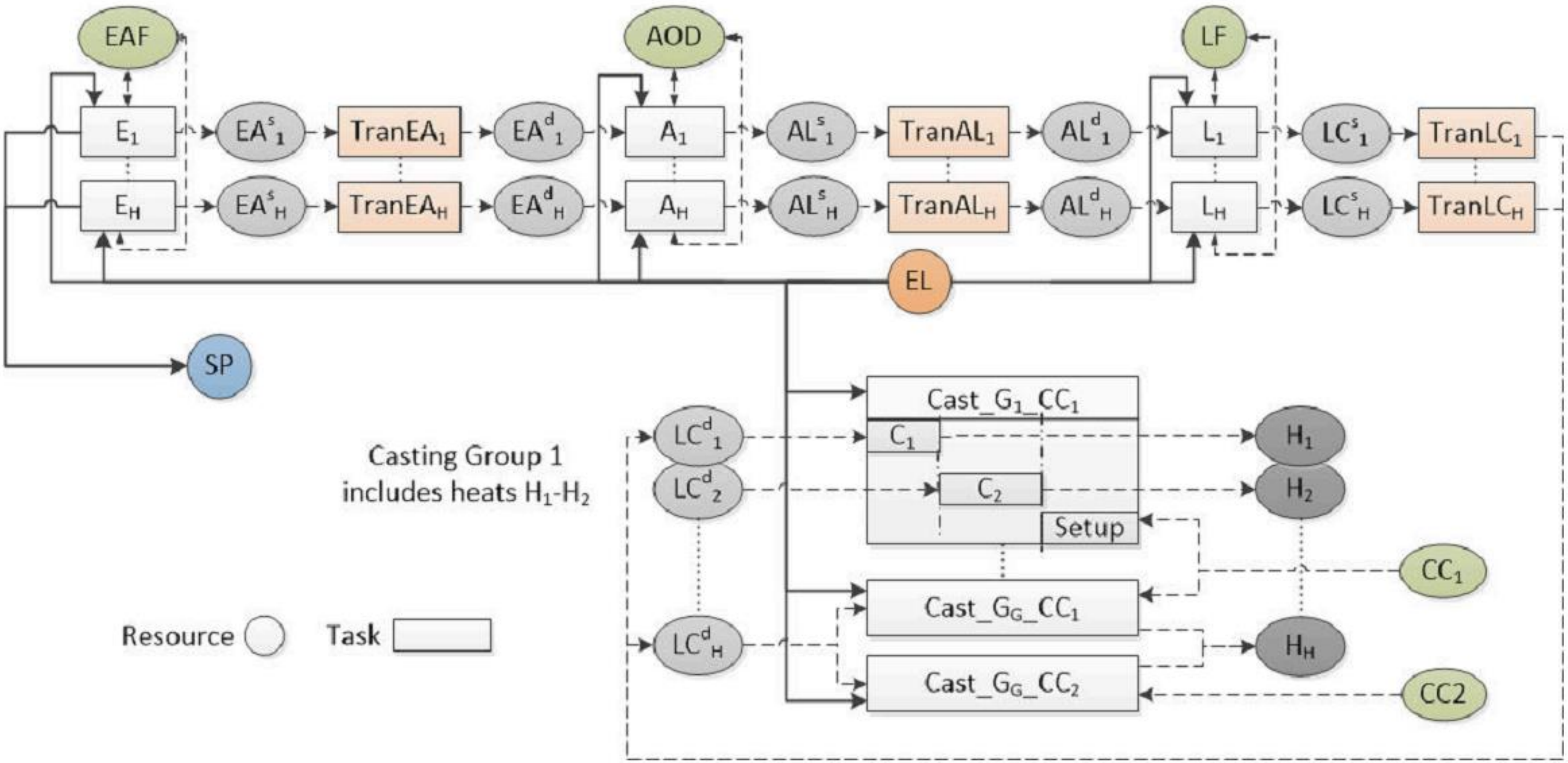
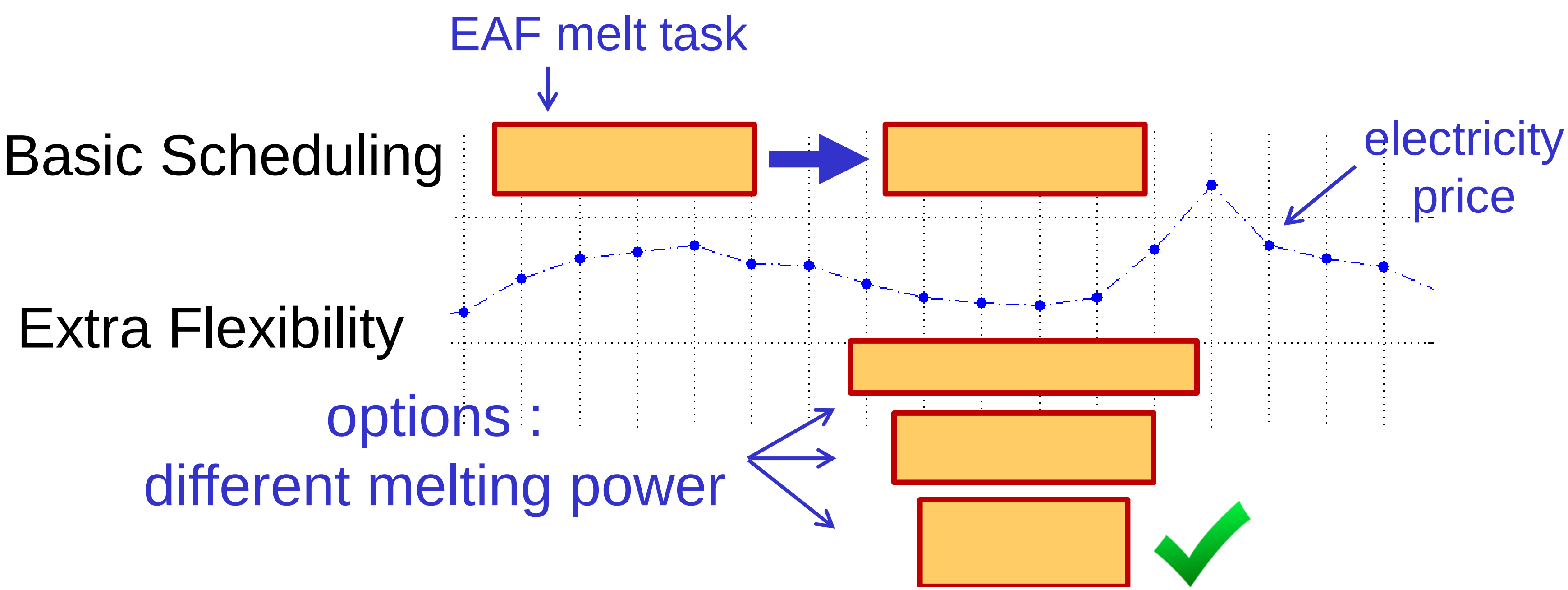


Fig. RTN for a steel plant.

Modeling Controllable Transformers [1]

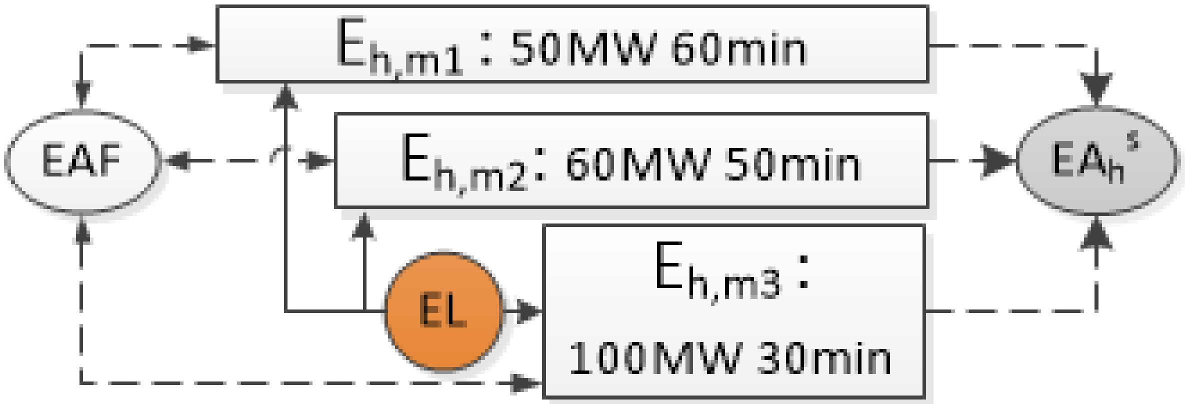
- Motivation - energy cost minimization scheduling
  - basic scheduling optimize by shifting the tasks
  - what about adjusting EAF's melting power ?
    - transformer's on-load tap changer (OLTC)



[1] X. Zhang, G. Hug, and I. Harjunkoski, "Cost-effective scheduling of steel plants with flexible EAFs," IEEE Transactions on Smart Grid, submitted.

Modeling Controllable Transformers

- Multiple melting modes
  - collect information of melting power options in EAF
    - each mode : specified tap position => melting power, duration
    - total energy : same for all modes
  - choose from multiple modes (tasks) for each heat



same heat, different modes, different tasks

Modeling Controllable Transformers

- Arbitrary flexible melting
  - the tap position can change at any time slot
    - v.s. Modes: change tap position at beginning for each heat
  - need extra variables (a lot!)
    - the melting power rate at each time slot
    - the ending of each melting task
      - the duration of melting is not known ahead => extra binary variables
  - need extra constraints (a lot!)
    - total energy consumption
    - melting power range

    ...

Steel Plant Parameters

EAF energy-intensive!

Table 1. Nominal power consumption [MW]

$d_{h,u}$	EAF_1	EAF_2	AOD_1	AOD_2	LF_1	LF_2	CC_1	CC_2
$power_{h,u}$	85	85	2	2	2	2	7	7

Table 2. Nominal process time [min]

Casting Group	$d_{h,u}$	EAF_1	EAF_2	AOD_1	AOD_2	LF_1	LF_2	CC_1	CC_2
G_1	$H_1 - H_4$	80	80	75	75	35	35	50	50
G_2	$H_5 - H_6$	85	85	80	80	40	40	60	60
	$H_7 - H_8$	85	85	80	80	20	20	55	55
G_3	$H_9 - H_{12}$	90	90	95	95	45	45	60	60
G_4	$H_{13} - H_{14}$	85	85	85	85	25	25	70	70
	$H_{15} - H_{16}$	85	85	85	85	25	25	75	75
G_5	H_{17}	80	80	85	85	25	25	75	75
	H_{18}	80	80	95	95	45	45	60	60
	H_{19}	80	80	95	95	45	45	70	70
	H_{20}	80	80	95	95	30	30	70	70
G_6	$H_{21} - H_{22}$	80	80	80	80	30	30	50	50
	$H_{23} - H_{24}$	80	80	80	80	30	30	50	60

[1] P. M. Castro, L. Sun, and I. Harjunkoski, “Resource task network formulations for industrial demand side management of a steel plant,”Industrial & Engineering Chemistry Research, vol. 52, no. 36, pp.13 046–13 058, 2013.

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Controllable Transformer Simulations

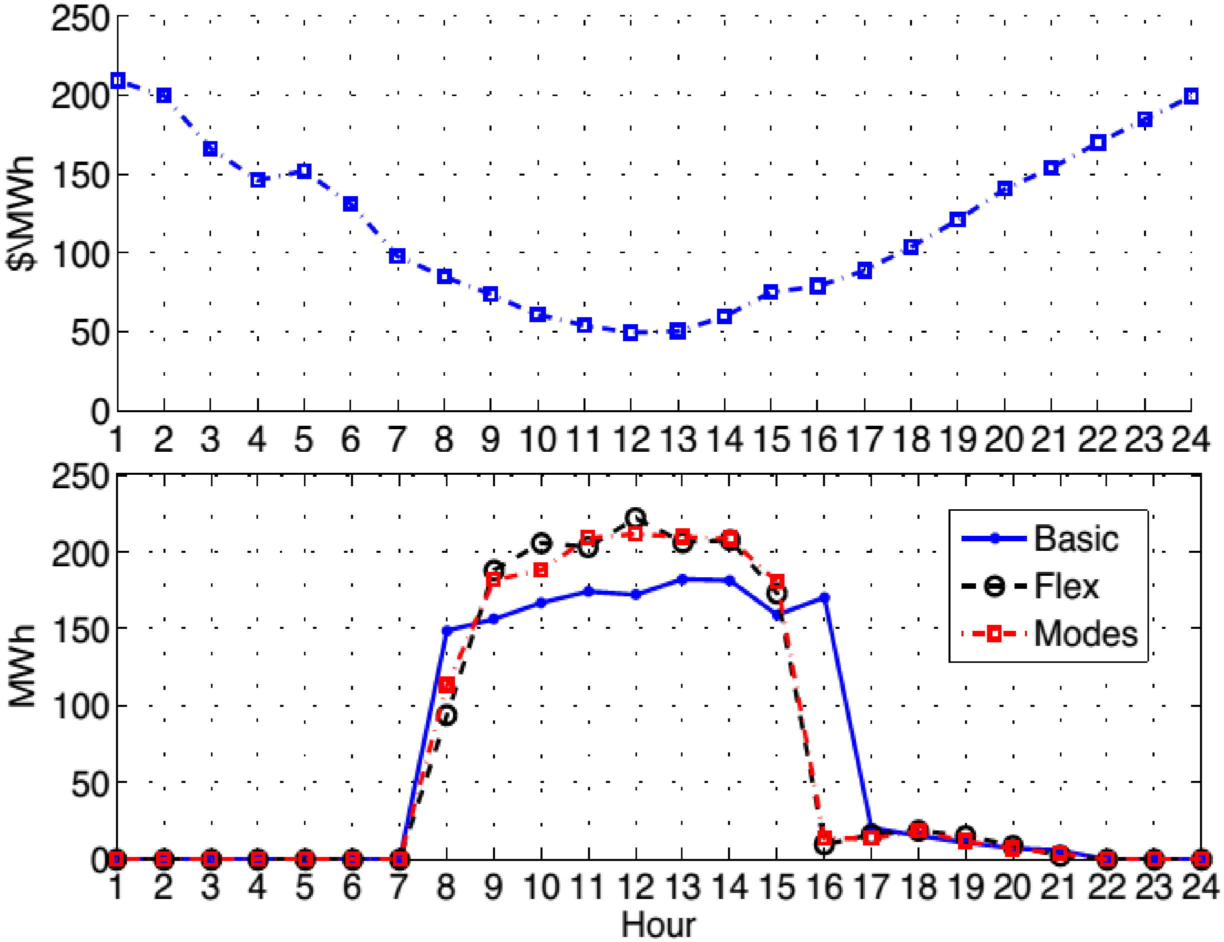


Fig. Hourly energy consumptions for scheduling 12 heats.

- with more flexibility, do better in utilizing price valley

- model Modes slightly different from Flex

Controllable Transformer Simulations

TABLE IV. Energy cost minimization with δ = 15min

Heats	Model	# bin	# var	# con	MIP(k$)	GAP	CPU(s)
4	Basic	2496	6048	3397	26.239	0	0.3
	Modes	3264	6816	3397	25.972	0	0.3
	Flex	2496	6816	4917	25.858	0	1.7
8	Basic	4992	11232	6122	60.173	0	0.8
	Modes	6528	12768	6122	57.501	0	1.1
	Flex	4992	12768	9162	57.332	0	31.1
12	Basic	7488	16416	8847	104.301	0	2
	Modes	10176	19104	8847	100.061	0	24
	Flex	7488	18720	13407	99.990	1.97%	7200
17	Basic	10560	22848	12253	171.615	0	4
	Modes	14208	26496	12253	159.454	0	170
	Flex	10560	26112	18713	160.896	3.72%	7200
20	Basic	12480	26784	14297	222.427	0	9
	Modes	16704	31008	14297	204.611	0	37
	Flex	12480	30624	21897	211.459	9.00%	7200
24	Basic	14976	31968	17022	299.782	0	320
	Modes	19968	36960	17022	277.283	0	83
	Flex	14976	36576	26142	287.077	11.36%	7200

- when flexibility increases:
complexity increases
CPU time increases
final obj decreases

- multiple modes:
a great tradeoff

Modeling Spinning Reserve Provision [1]

- Optimization model
  - minimize net cost
    - energy cost minus spinning reserve revenue
  - subject to
    - resource balance (add SP resource and its interactions)
    - task execution
    - intermediate product waiting time
    - final product delivery due time

=> a large scale mixed integer programming problem

[1] X. Zhang, G. Hug, Z. Kolter, and I. Harjunkoski, "Industrial demand response by steel plants with spinning reserve provision," in 47th North American Power Symposium, 2015

Hourly Prices and Reserve Provision

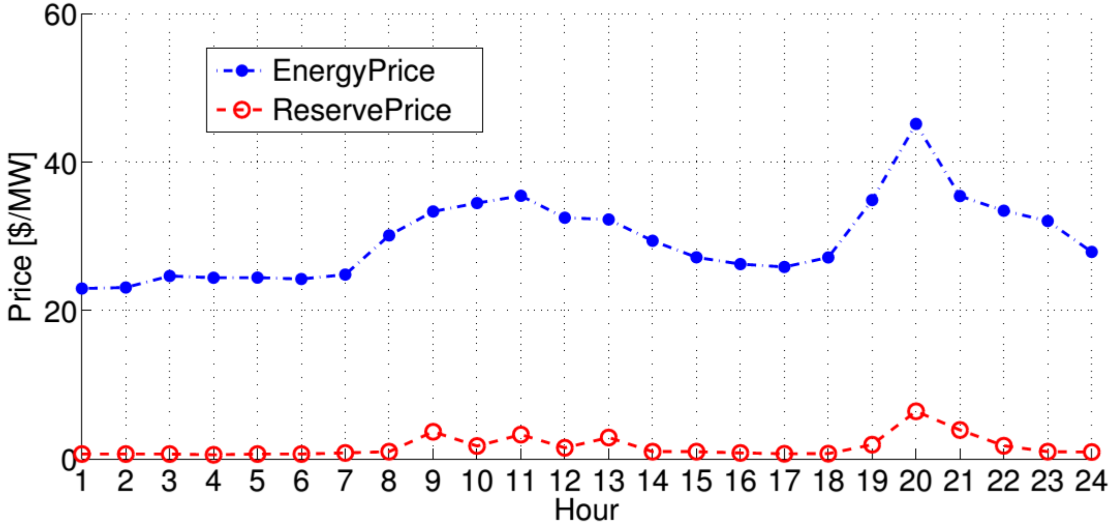


Fig 1. Energy and reserve prices

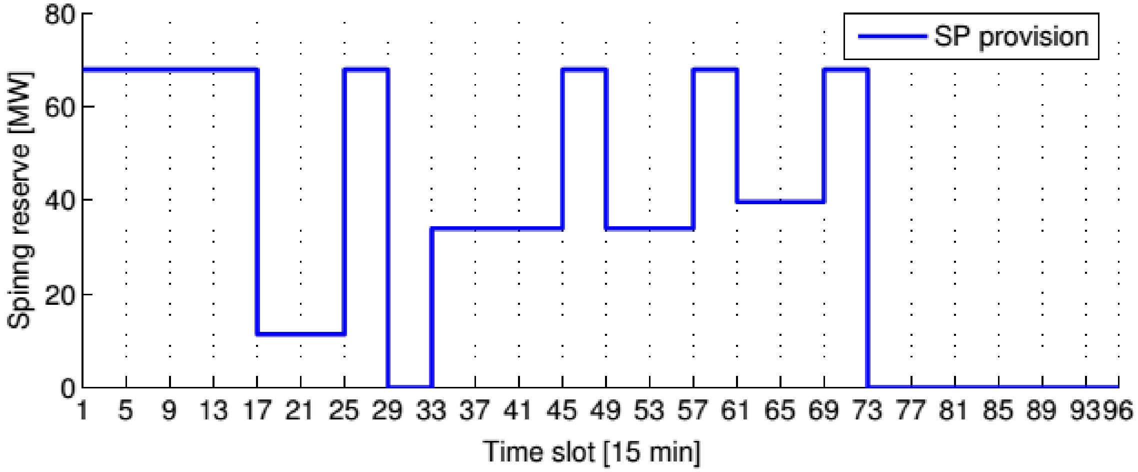


Fig 2. Hourly SP provision.

- Feb 6, 2014, MISO

- provides as much as 70 MW SP

Spinning Reserve Provision Results

Optimization results with t_0 = 15min

Groups	w/o SP Obj(k$)	with SP Obj(k$)	with SP EN Cost(k$)	with SP SP Revenue(k$)
1-3	39.307	39.002	39.321	0.319
1-4	57.824	57.357	57.864	0.507
1-5	69.731	69.157	69.897	0.741
1-6	86.346	85.508	86.474	0.966

- with SP:
EN cost increases
net cost decreases

Optimization results with t_0 = 10min

Groups	w/o SP Obj(k$)	w/o SP CPU Time(s)	with SP Obj(k$)	with SP CPU Time(s)
1-3	39.041	397.7	38.651	739.7
1-4	57.517	637.8	57.009	1094.7
1-5	69.162	7200.0	68.468	7200
1-6	85.228	916.0	84.164	3569.7

- a finer time grid:
net cost decreases
CPU time increases

Tailored Branch and Bound Algorithm [1]

- Classical B&B
  - branch
    - branch on starting times of tasks
    - constraints set C
      - time restriction (a_{k1}, b_{k1})
      - starting time for task $k1$ is between a_{k1}, b_{k1}

$$C = [(a_{k1}, b_{k1}), (a_{k2}, b_{k2}), \ldots, (a_K, b_K)]$$

$$x_{k1,t} = \begin{cases} 1, & \text{if } a_{k1} \leq t < b_{k1} \\ 0, & \text{otherwise} \end{cases}$$

function CC = Branch-Nodes(C)
  if $C == \{\}$:
    CC = set()
    enumerate parallel units:
      CC.add($[(0,T), \ldots, (0,T)]$)
  else:
    $k^* \leftarrow \arg\max_k (b_k - a_k)$
    $m^* \leftarrow \text{int}(\frac{b_{k^*} - a_{k^*}}{2})$
    $CC = \{[(a_{k1}, b_{k1}), \ldots, (a_{k^*}, m^*), \ldots],$
      $[(a_{k1}, b_{k1}), \ldots, (m^*, b_{k^*}), \ldots]\}$
  return CC

Alg. Classical branching for steel scheduling.

[1] X. Zhang, G. Hug, Z. Kolter, and I. Harjunkoski, "Computational approaches for efficient scheduling of steel plants as demand response,"in IEEE Power System Computation Conference, submitted.

Tailored B&B

- Basic idea
  - consistent process orders
    - for heats within same group
  - tasks within same group
    - leader and followers
      - first heat v.s. others
    - only branch leader task
    - restrict followers by rules
  - dictionary O
    - describe relationship
  - complexity reduced
    - T^K => T^L

(K, L : the number of tasks, leader tasks
T : the number of time slots)

function CC = Branch-Nodes(C)
  if $C == \{\}$:
    CC = set()
    enumerate parallel units:
      CC.add($[(0,T),\ldots,(0,T)]$)
    return CC
  $k^* \leftarrow \arg\max_{k \in O.\text{keys}}(b_k - a_k)$
  if $b_{k^*} - a_{k^*} > \epsilon_d$:
    $m^* \leftarrow \text{int}(\frac{b_{k^*} - a_{k^*}}{2})$
    $o_a, o_b \leftarrow$ offset for followers in $O[k^*]$
    $CC = \{[\ldots,(a_{k^*}, m^*),(a_{k^*}+o_a, m^*+o_b),\ldots$
        $[\ldots,(m^*, b_{k^*}),(m^*+o_a, b_{k^*}+o_b),\ldots$
  else:
    $k^* \leftarrow \arg\max_{k \in \mathbb{K}}(b_k - a_k)$
    $m^* \leftarrow \text{int}(\frac{b_{k^*} - a_{k^*}}{2})$
    $CC = \{[(a_{k1}, b_{k1}),\ldots,(a_{k^*}, m^*),\ldots],$
        $[(a_{k1}, b_{k1}),\ldots,(m^*, b_{k^*}),\ldots]\}$

Alg. Tailored branching.

$$O[k_{E1}] = \{k_{E2} : (0, \tau_{E1}),\ k_{E3} : (\tau_{E1}, \tau_{E1}),\ k_{E4} : (\tau_{E2}, \tau_{E1}+\tau_{E2})\}$$

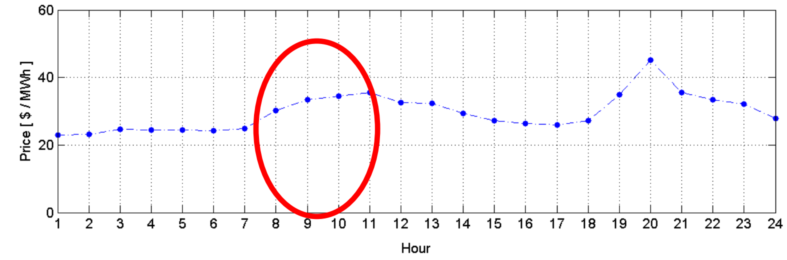
offsets/delays between leader and its followers

Tailored B&B

- Performance

BRANCH AND BOUND RESULTS WITH t_0 = 15MIN

Groups		c0	b1	
G1-2	Obj(k$)	24.553	24.698	1.006
	CPU(s)	5.8	6.2	
	lpNum	2460	57	
G1-3	Obj(k$)	39.306	39.665	1.009
	CPU(s)	155.4	50.0	
	lpNum	9071	228	
G1-4	Obj(k$)	57.857	58.694	1.014
	CPU(s)	60.4	197.8	
	lpNum	3852	280	
G1-5	Obj(k$)	69.737	70.194	1.007
	CPU(s)	4.3	861.0	
	lpNum	0	478	
G1-6	Obj(k$)	86.352	86.799	1.006
	CPU(s)	104.9	2737.6	
	lpNum	3698	725	



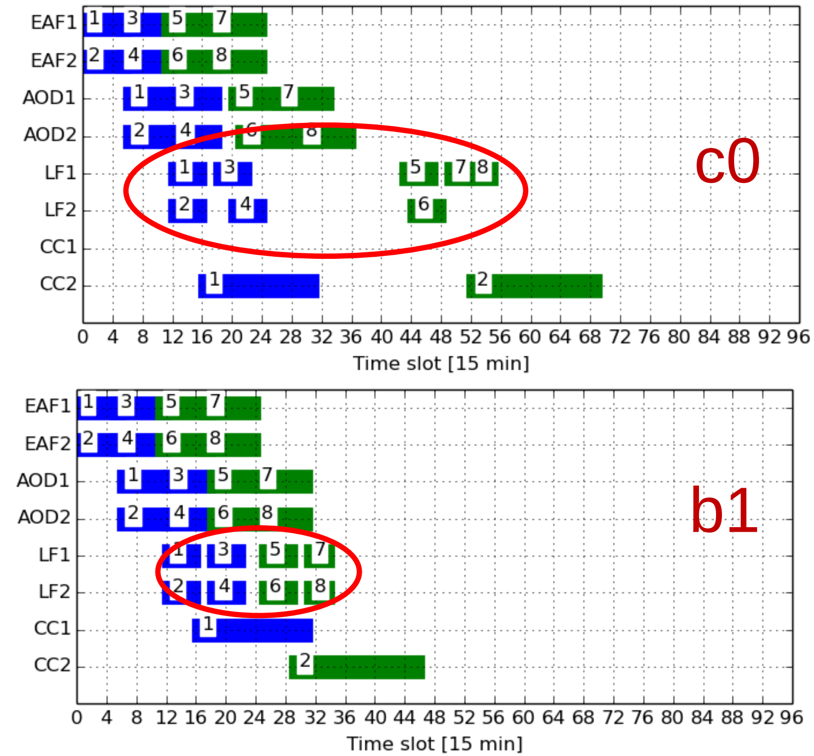


Fig. Scheduling results comparison.

- c0: cplex,   b1: tailored b&b
- significantly reduces iteration
- optimality loss around 1%

Handle Complexity of Process

- Timeline
  - 14.01-14.06, Modeling Controllable Transformers
  - 14.07-14.12, Modeling Spinning Reserve Provision
  - 15.01-15.06, Tailored Branch and Bound Algorithm
  - 15.07-15.12, Reserve Dispatch and Melting Curves
    - consider actual dispatch of reserve and realistic melting curves
  - 16.01-16.06, Transportation between Stages
    - consider various transport modes and exact equipment locations

Outline and Proposed Approach

- Introduction of Electricity Markets
- Account for Uncertainty
  - Optimize Regulation Capacity
  - Optimal Bidding of Energy and Reserve
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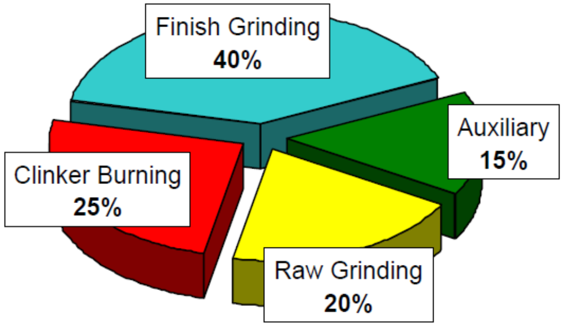
  - Modeling Spinning Reserve Provision
  - Tailored Branch and Bound Algorithm
- Overcome Granularity Restriction
  - MPC Coordination of Loads and Storage

Cement Plant



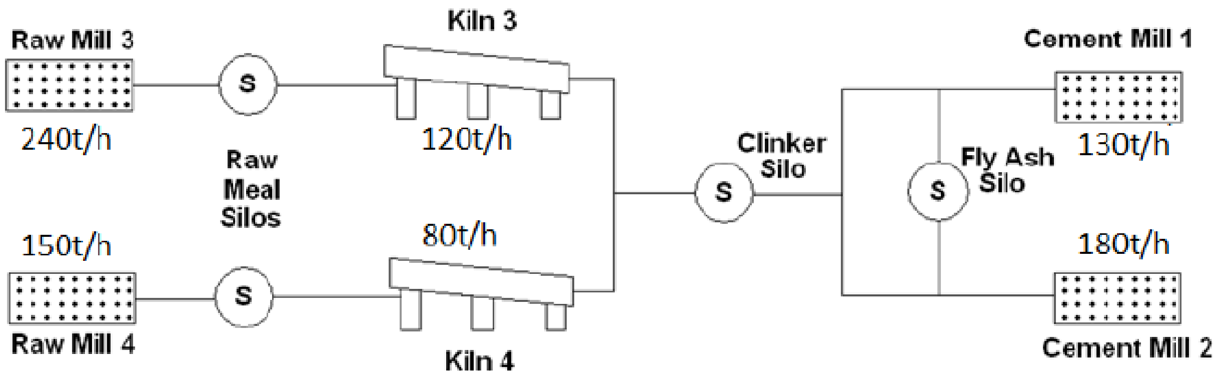


Fig. (Left) Energy distribution among cement manufacturing process [1]
(Top) A typical cement plant layout in South Africa [2]

- Energy intensive
  - energy 40% of total cost [3], net profit margin only 2.03% [4]
    - providing regulation helps to further reduce net cost
      - e.g. consider a 10MW crusher, produce 200 ton cement per hour
      - electricity market prices[5] (approximately)
        - » energy $30/MWh, spinning reserve $1/MW, regulation $10/MW
      - 10 MW in energy + spinning reserve : $(250-10)/200ton = $1.2/ton
      - 5 MW in energy + regulation : $(125-50)/100ton = $0.75/ton

[1] 2011, Load-shifting opportunities for a typical South African cement plant.
[2] 2007, TAMU-PhD-Thesis, Improved cement quality and grinding efficiency by means of closed mill circuit modeling.
[3] 2008, Greening the construction industry: Enhancing the performance of cements by adding bioglycerol
[4] 2010, http://www.bloomberg.com/bw/slideshows/20110118/most-and-least-profitable-business-types#slide10
[5] 2015, https://www.misoenergy.org/MarketsOperations/RealTimeMarketData/Pages/AncillaryMarketMCP.aspx

Mill (crusher)

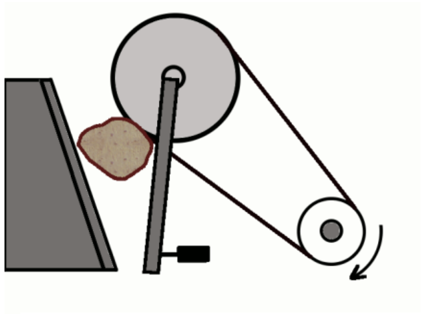


Fig 1. Jaw crusher [1]

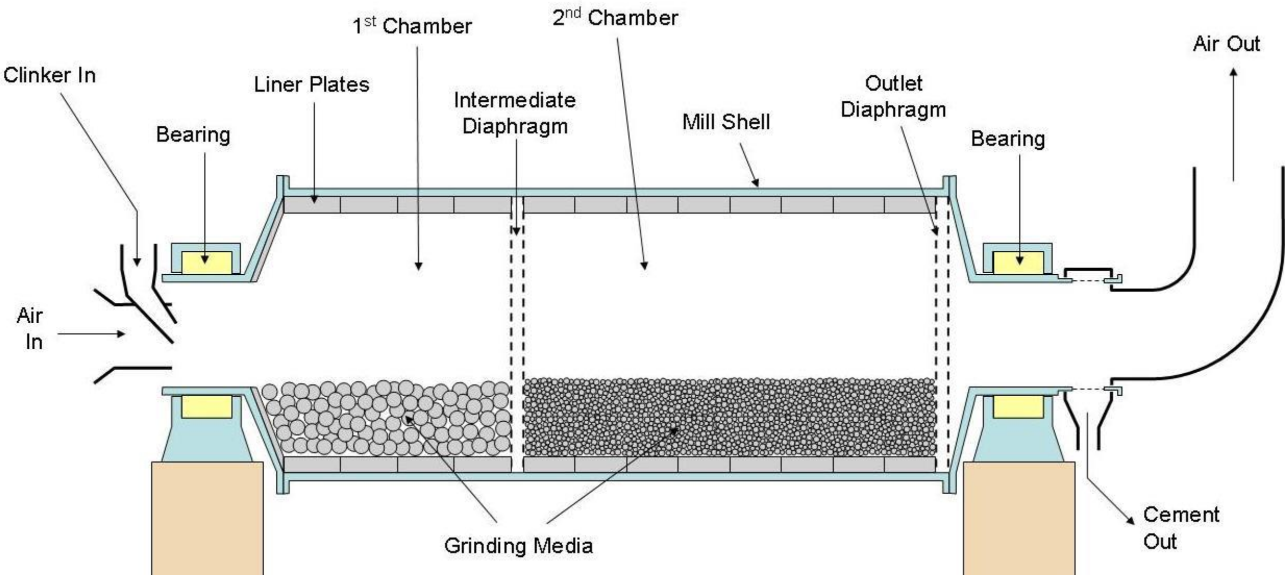


Fig 2. Ball mill layout [2]

- Flexibility
  - shut-down and start-up of the mill motor [3]
    - without excessive inconvenience
  - spinning reserve provision [4]
  - fast enough for regulation, load following
    - switch on/off within seconds

[1] https://en.wikipedia.org/wiki/Crusher [2] https://en.wikipedia.org/wiki/Cement_mill
[3] 2011, Load-shifting opportunities for a typical South African cement plant.
[4] 2012, Robust integer optimization and scheduling problems for large electricity consumers.

MPC Coordination of Loads and Storage [1]

- Regulation (or load following)
  - continuous, AGC signal
- Cement plant flexibility
  - fast, but not fine enough, several MWs/step
- Coordination
  - cement mills/crushers + on-site storage/battery
    - crushers, large/discrete power change, main body
    - battery, fine/continuous power change
  - model predictive control (MPC)
    - decides the switch on/off of the crushers
    - based on a prediction of the upcoming AGC signal

[1] X. Zhang, G. Hug, Z. Kolter, and I. Harjunkoski, “Model predictive control of industrial loads and energy storage for demand response,”in IEEE Power and Energy Society General Meeting, submitted.

MPC Framework

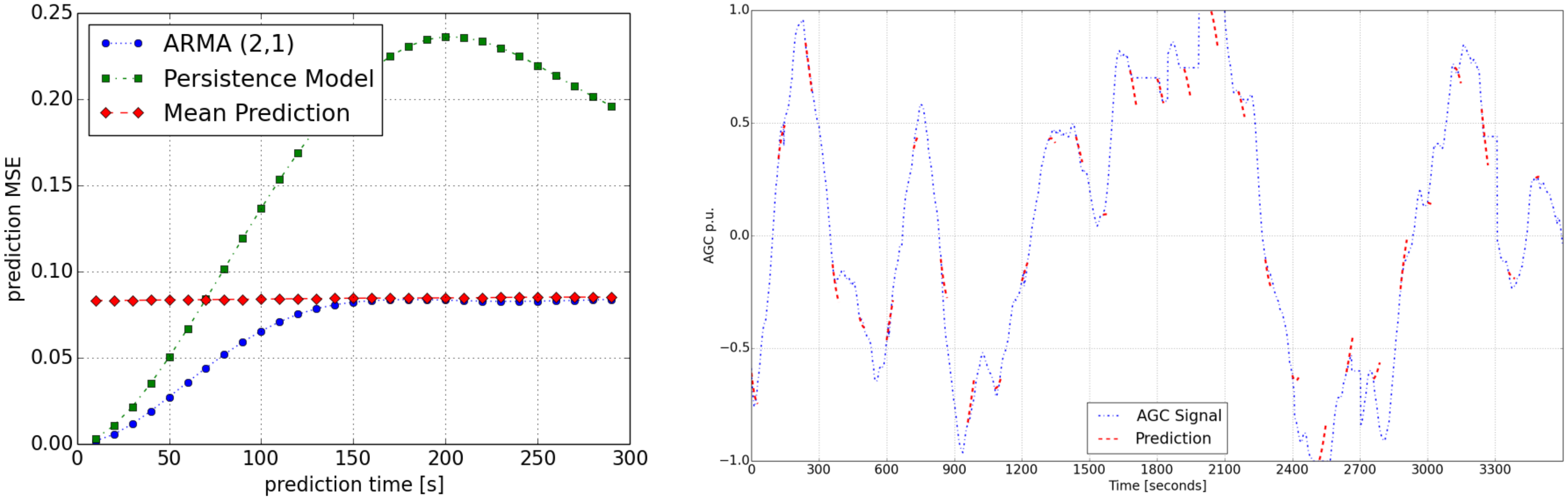


Fig 1. AGC signal and ARMA prediction.

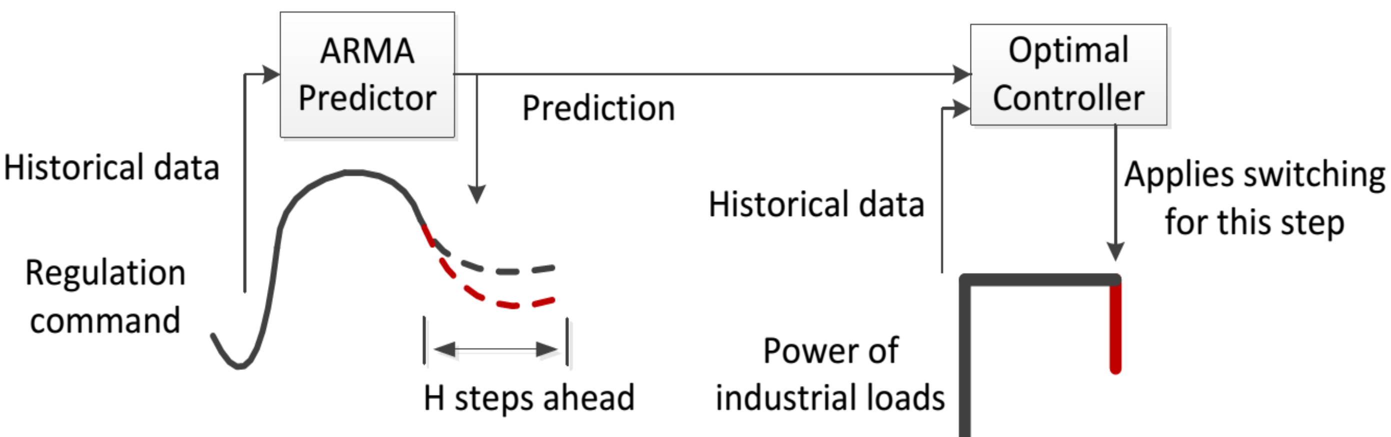


Fig 2. MPC coordination framework

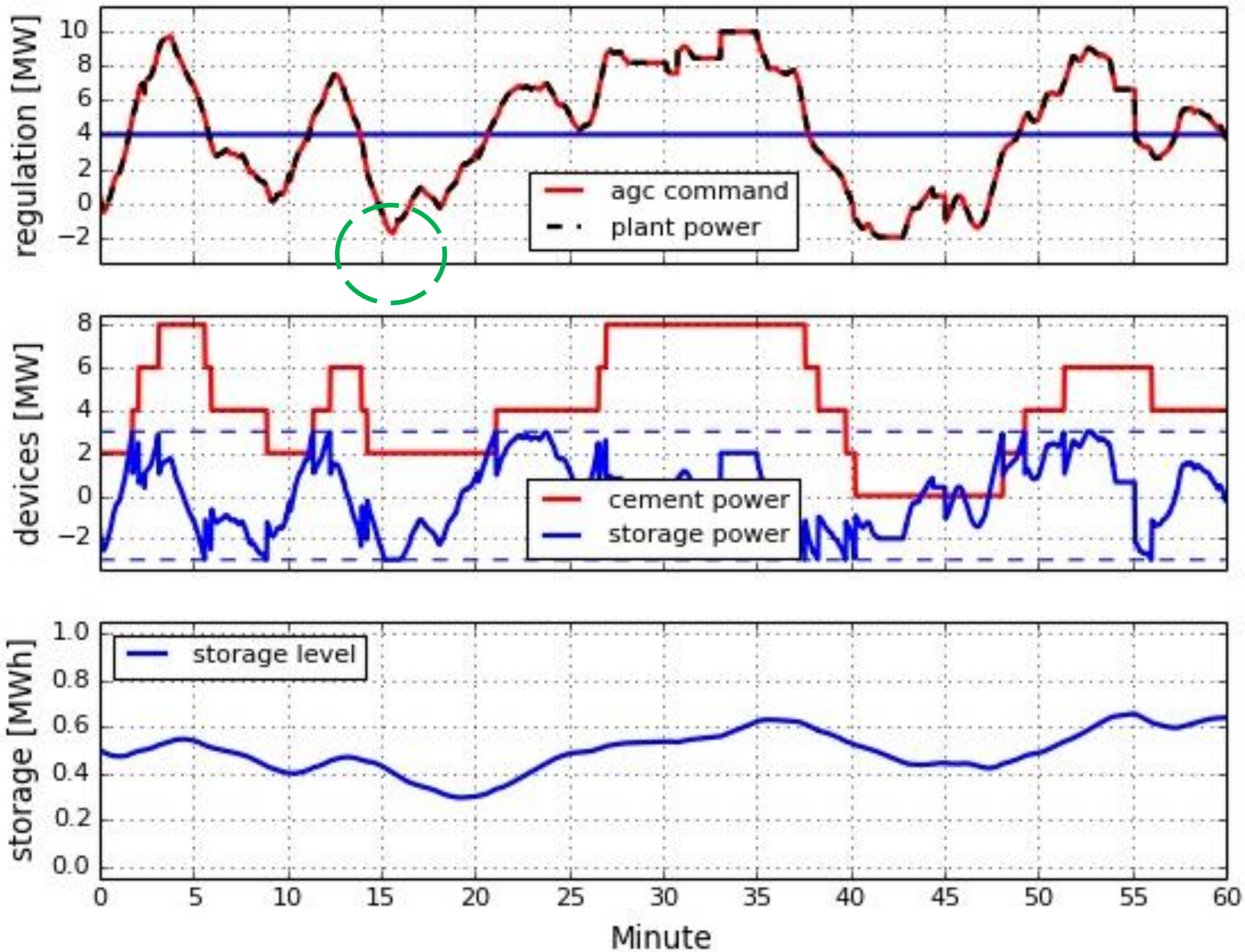
MPC Simulation

- Optimal controller
  - given regulation capacity and power baseline
  - optimizes coordination between crusher and battery
  - minimize
    - regulation mismatch, crusher switching, battery level deviation
  - subject to
    - battery energy balance, maximum switch number limitation
- Case study
  - cement plant : 4 crushers, each has 2MW
  - on-site storage [1] : 1MWh, -3MW~3MW, no efficiency loss
  - capacity 6MW, baseline 4MW, i.e. range [-2, 10] MW

[1] 2012, Frequency Response from Autonomous Battery Energy Storage

MPC Simulation Result

Simulation settings:
H = 15



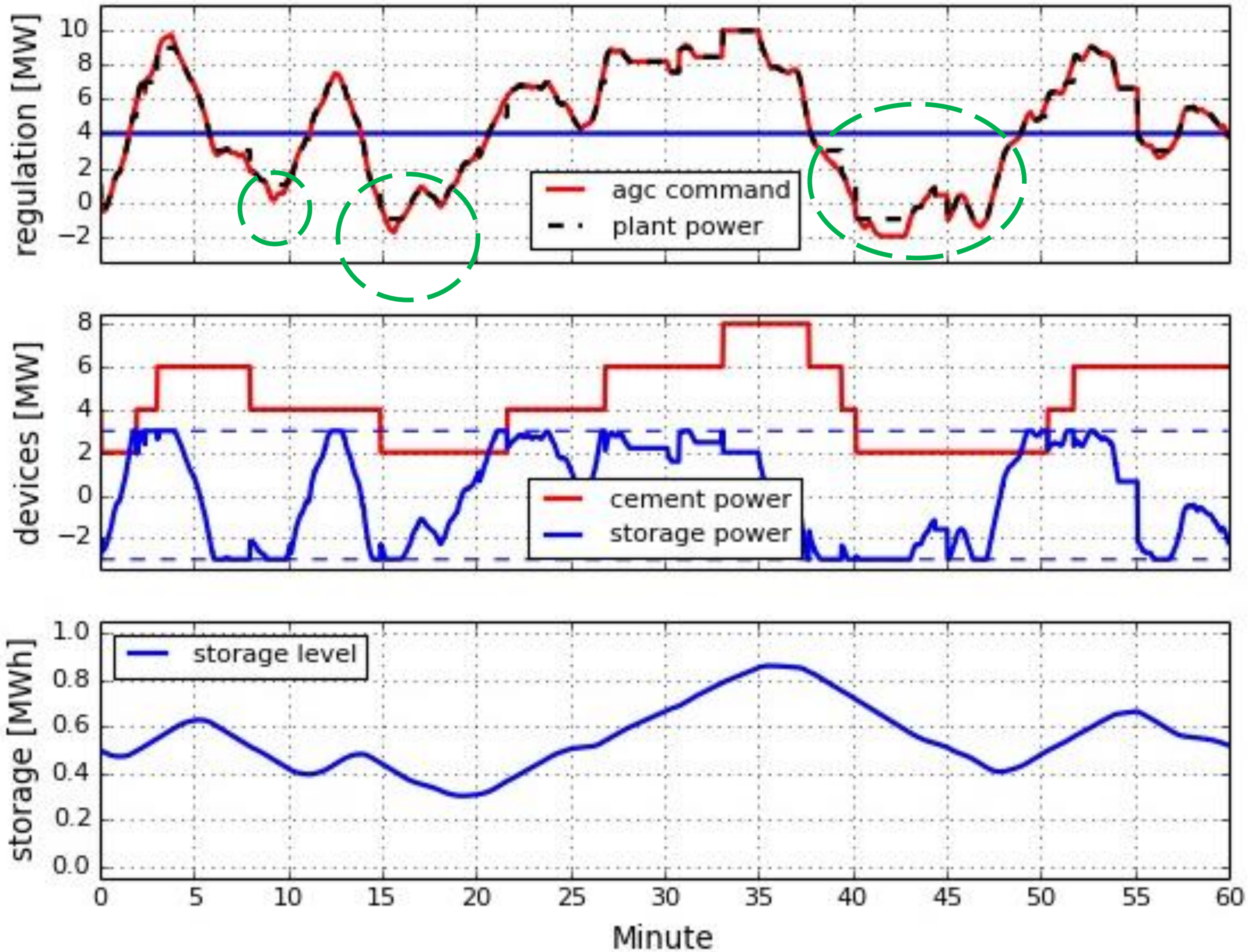
mismatch
0.01 MWh

switch
21 times

delta
0.1 MWh

Changing Penalties

Simulation settings:
switch penalty 200



mismatch
0.12 MWh

switch
12 times

delta
0.0 MWh

Overcome Granularity Restriction

- Timeline
  - 15.07-15.12, MPC Coordination of Loads and Storage
  - 16.01-16.06, Scheduling with Regulation Provision
    - consider the processing rate of the kilns and the storage capacity of the silos.

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Questions & Discussions

Thanks!

backup slides

Research Gap

- Power and Energy communities
  - the integration of DR into power system
  - residential and commercial loads
- Chemical Engineering communities
  - the potentials from chemical processing plants as DR
  - electric energy markets
- Research gap
  - the integration of industrial DR into power system
  - esp. industrial DR in ancillary service markets
    - reserve, regulation, load following

RTN for Steel Plants - Resources

Consider heat h

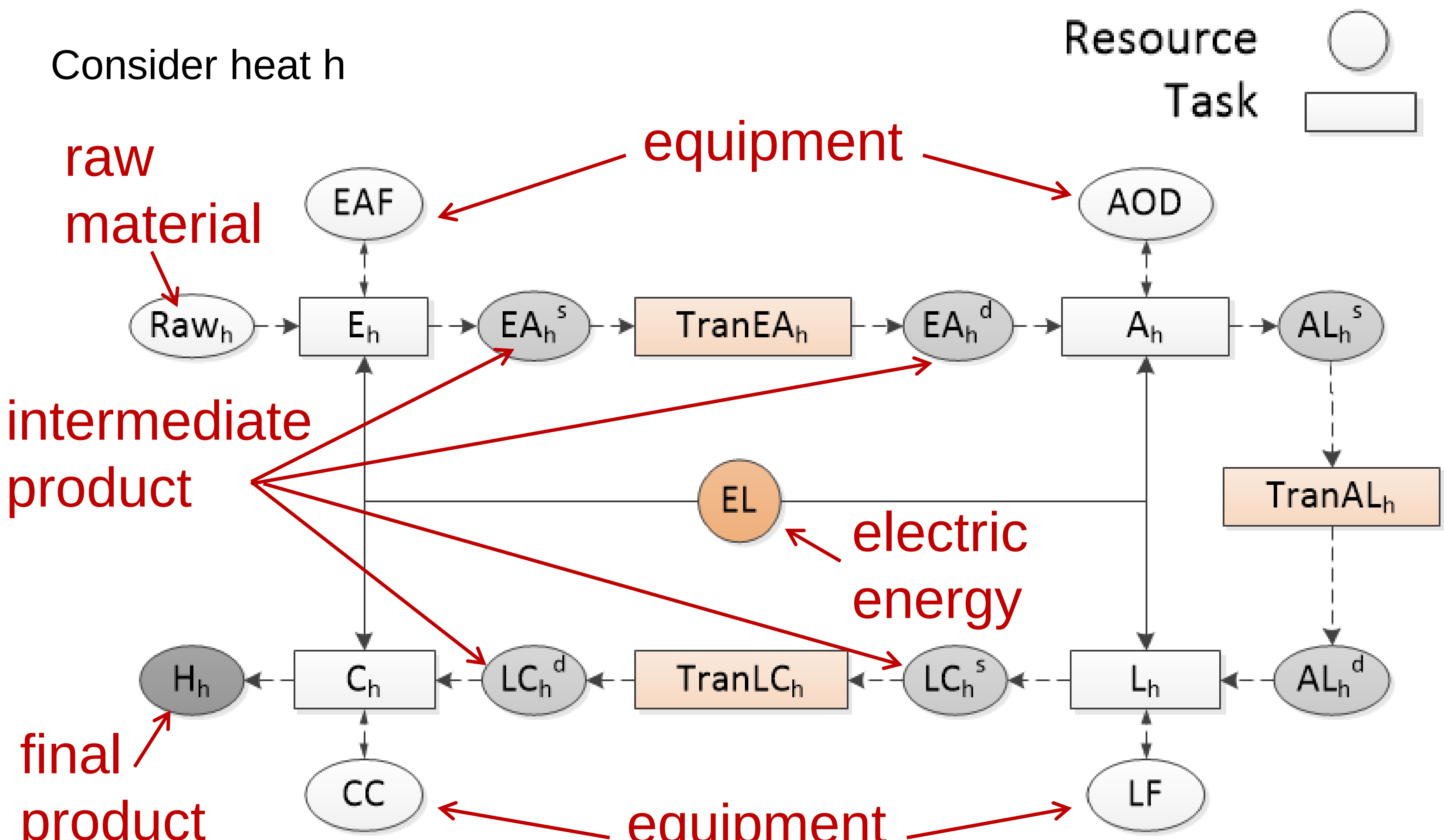


Fig. Illustration of RTN for a steel plant.

RTN for Steel Plants

- Tasks

Consider heat h

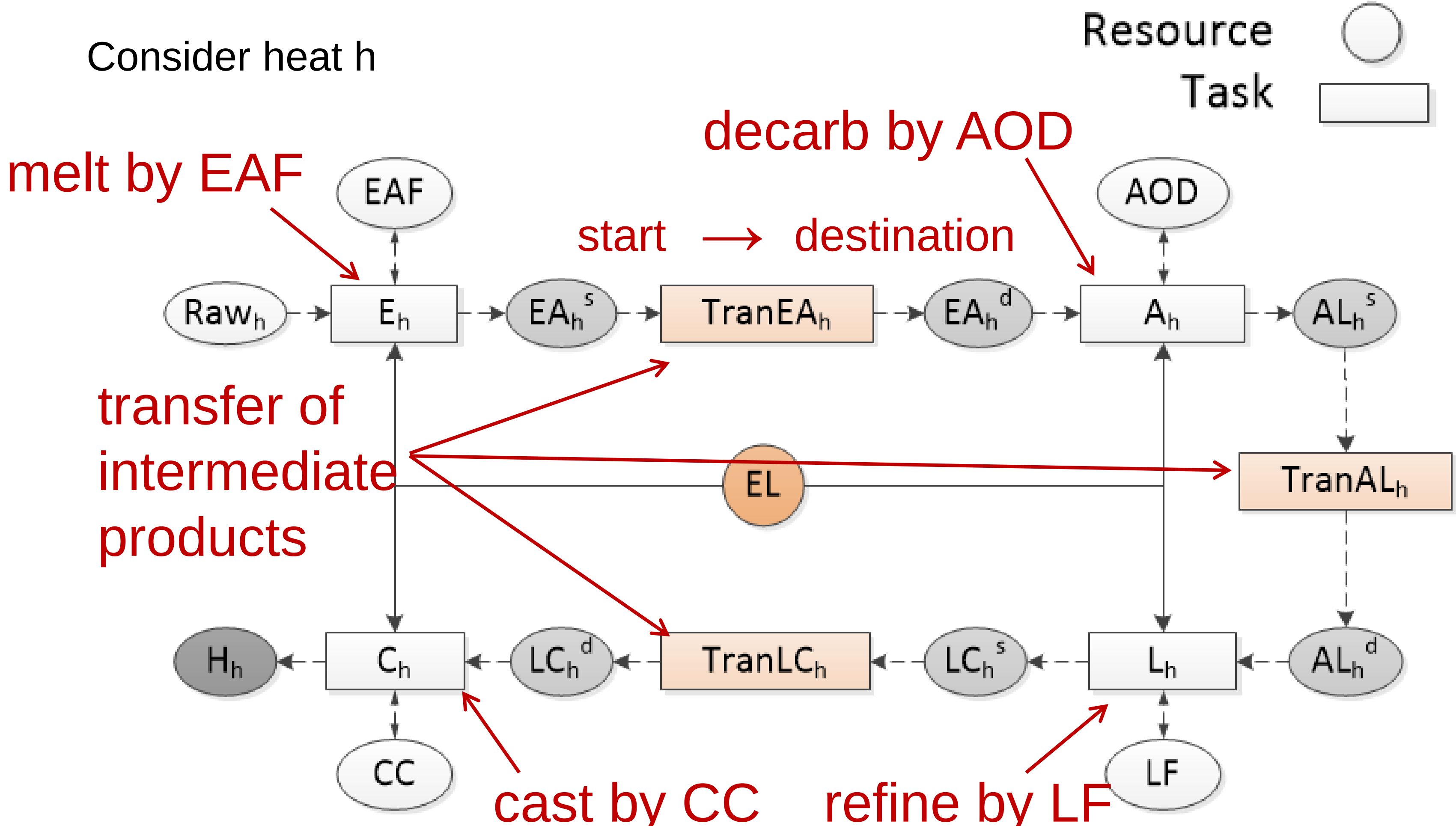


Fig. Illustration of RTN for a steel plant.

RTN for Steel Plants

- Interactions

Consider heat h

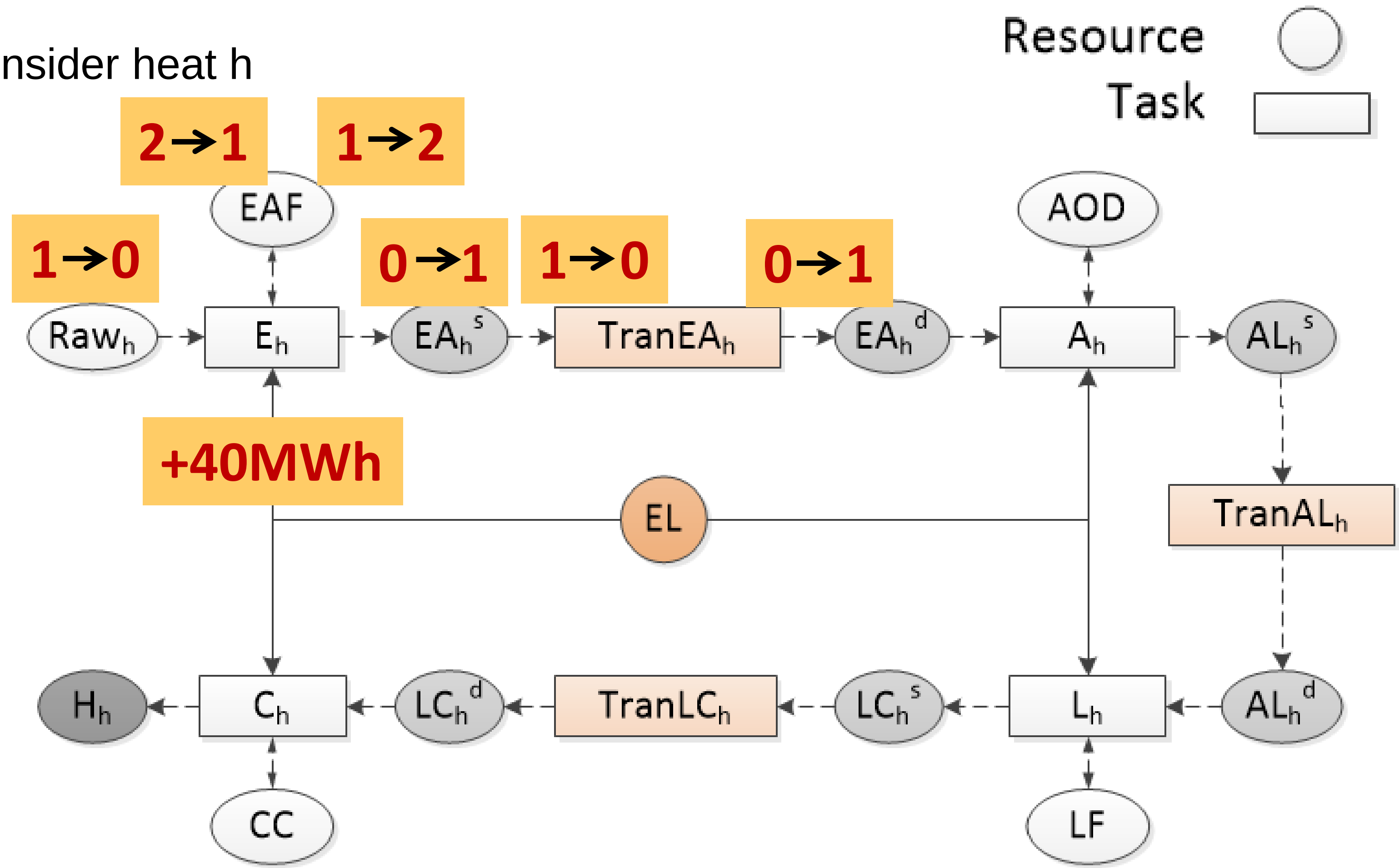
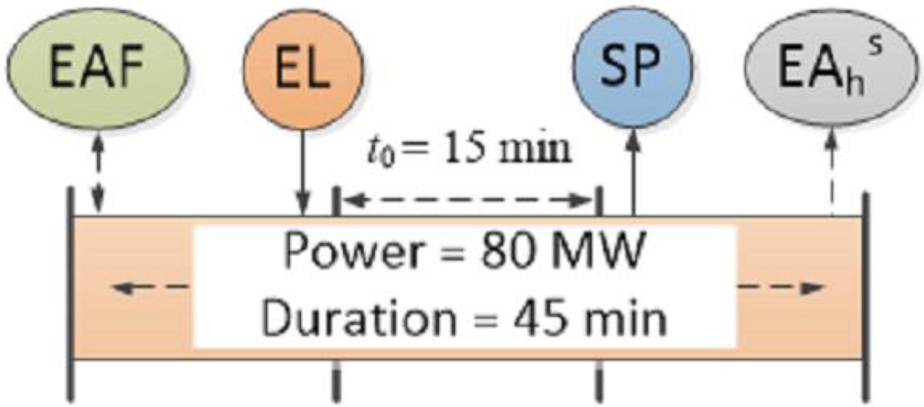


Fig. Illustration of RTN for a steel plant.

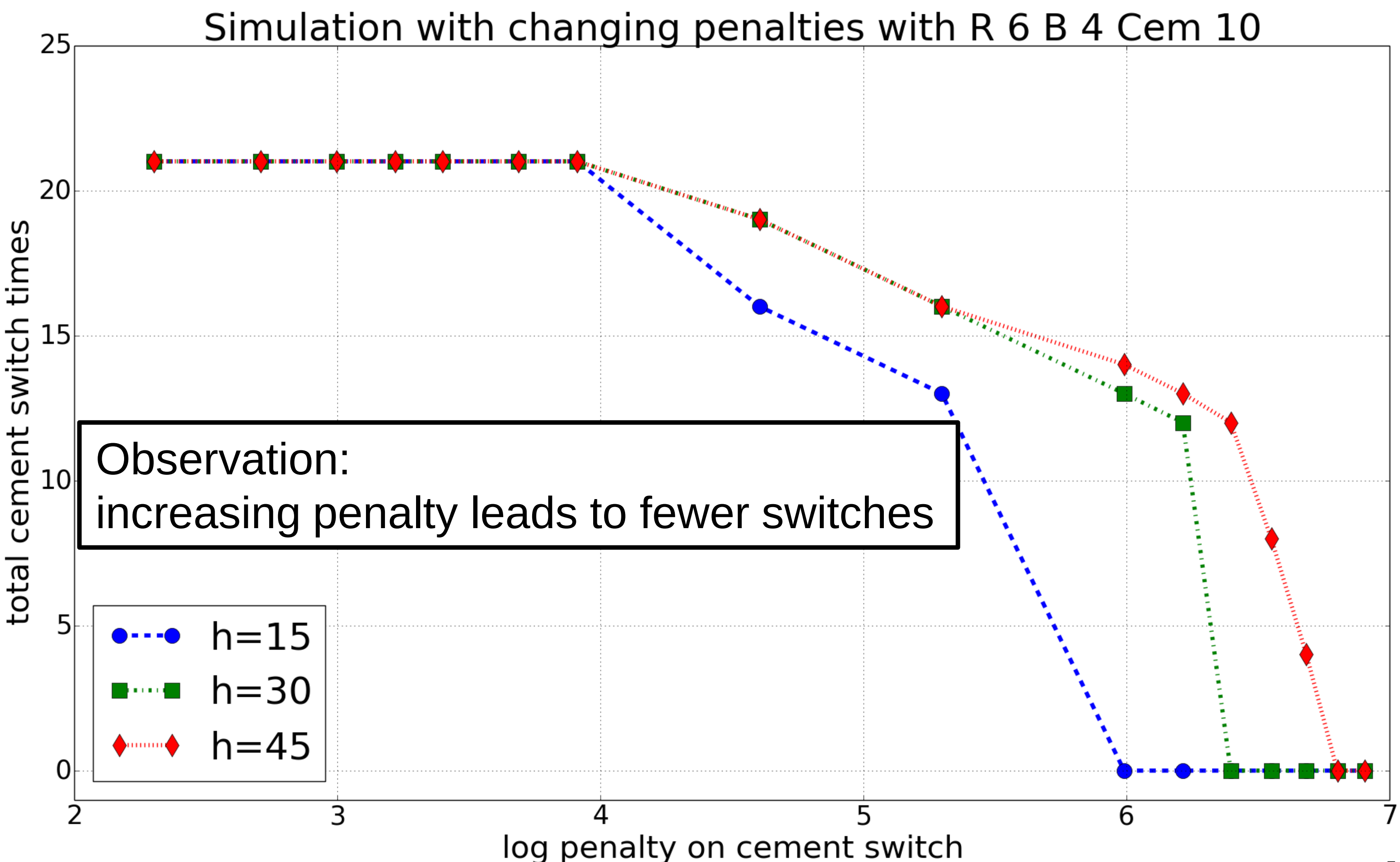
Interaction Parameter



$$\Delta^{E_h} = \begin{array}{cl} \begin{array}{cccc} \theta = 0 & 1 & 2 & 3 \end{array} & \\ \begin{bmatrix} -1 & 0 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots \\ 20 & 20 & 20 & 0 \\ 32 & 32 & 32 & 0 \end{bmatrix} & \begin{array}{l} \mathrm{EAF} \\ \\ \mathrm{EA}_h^s \\ \\ \mathrm{EN}\ [\mathrm{MWh}] \\ \mathrm{SP}\ [\mathrm{MW}] \end{array} \end{array}$$

Changing Penalties

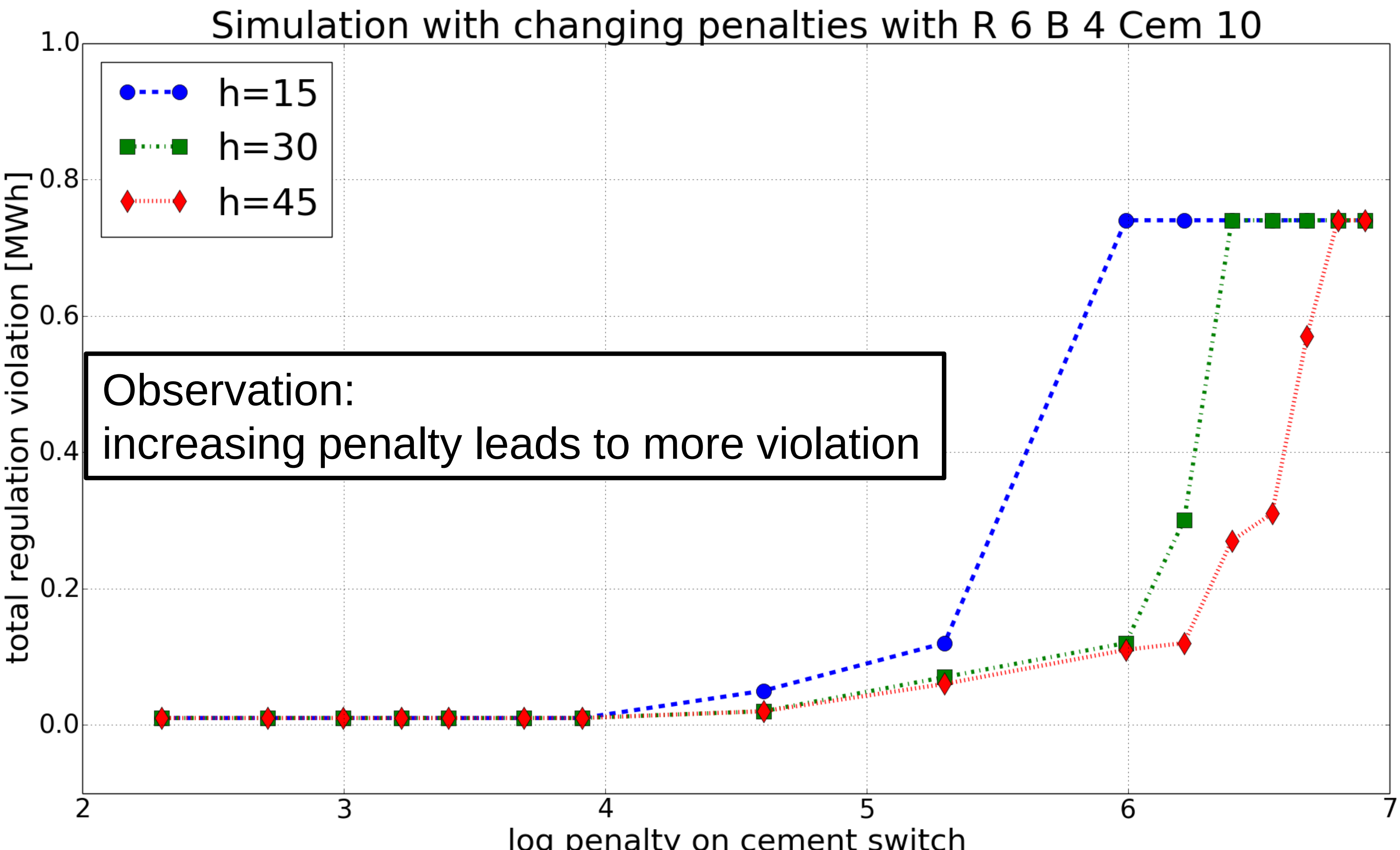
Simulation settings:
other penalties fixed at 10



Observation:
increasing penalty leads to fewer switches

Changing Penalties

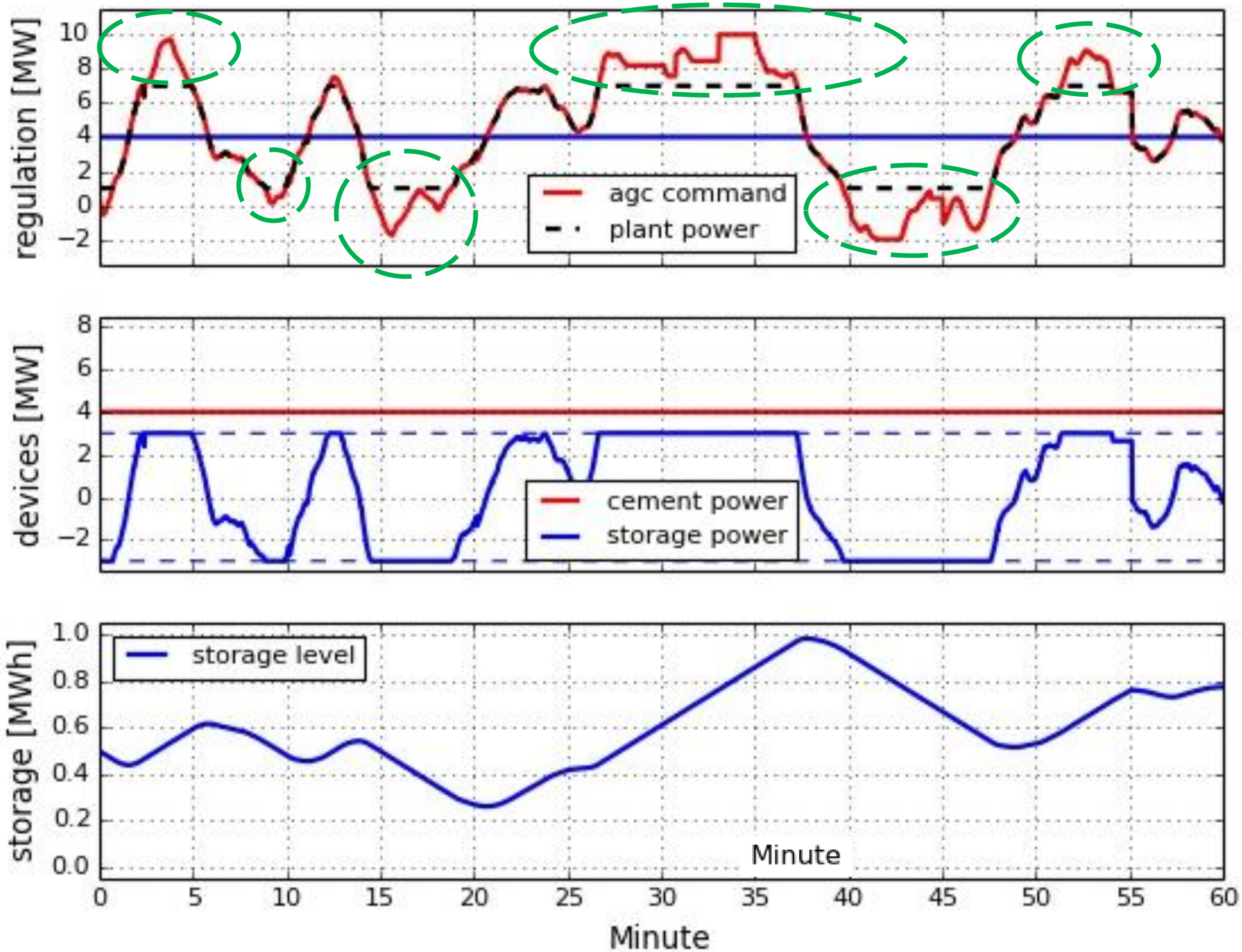
Simulation settings:
other penalties fixed at 10



Observation:
increasing penalty leads to more violation

Changing Penalties

Simulation settings:
switch penalty 1000



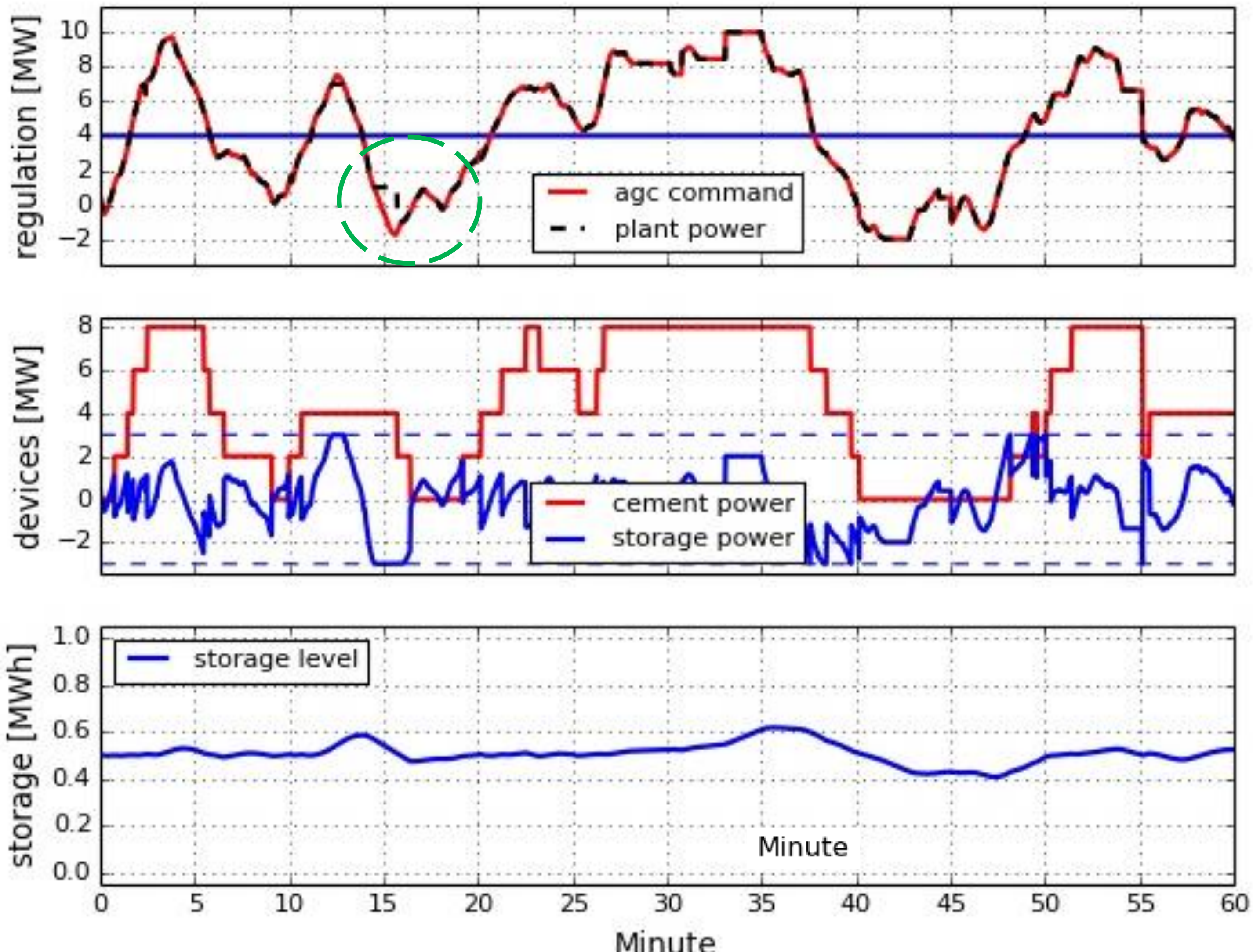
violation
0.74 MWh

switch
0 times

delta
0.3 MWh

Changing Penalties

Simulation settings:
deviation penalty 1000



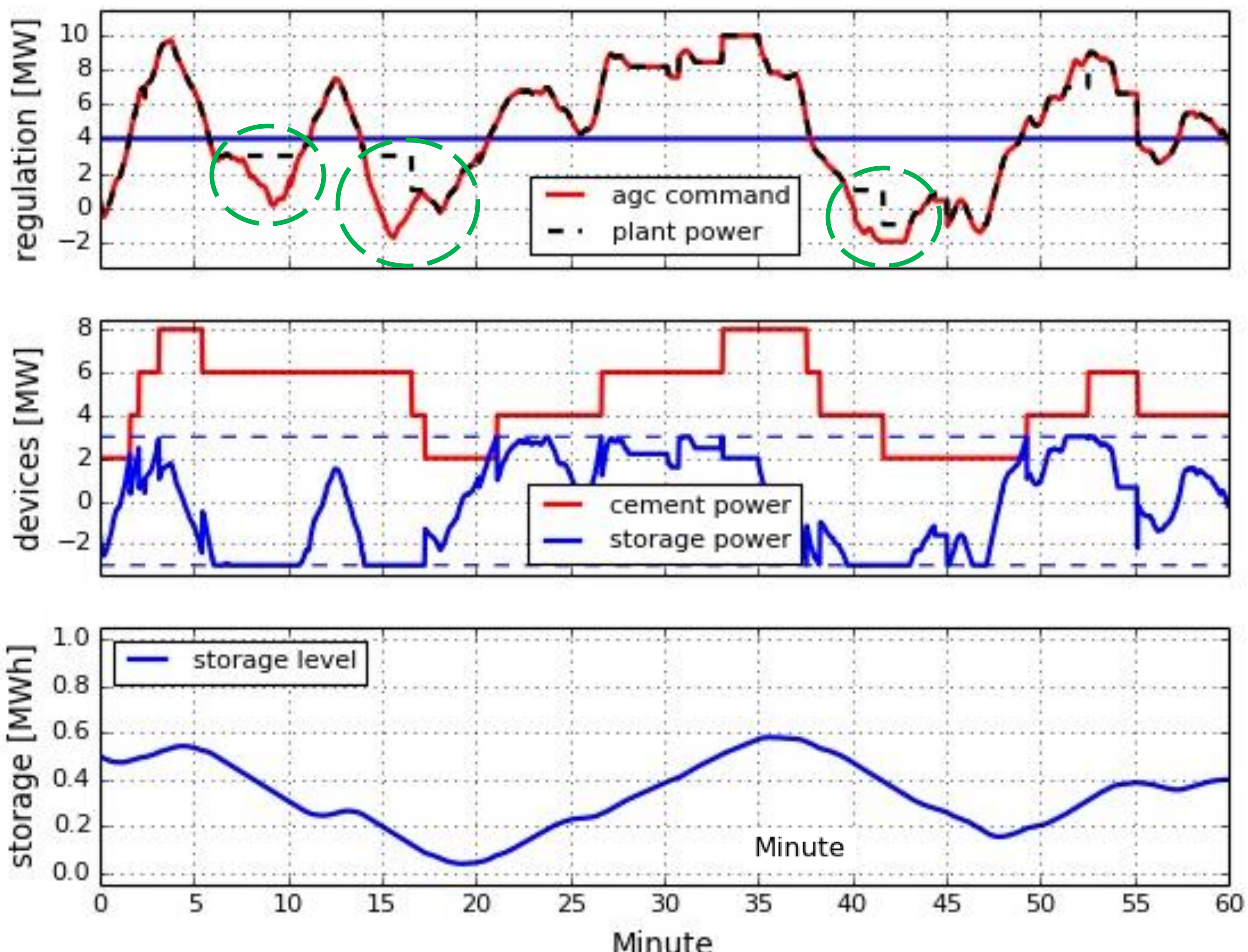
violation
0.04 MWh

switch
34 times

delta
0.0 MWh
level between
0.4, 0.6

Changing Penalties

Simulation settings:
switch limit 4 times within 5 mins



violation
0.35 MWh

switch
15 times

delta
0.1 MWh
level between
0.0, 0.6

Open Questions

- Applications to other industries
  - air separation units, paper & pulp, ...
- Electricity markets redesign
  - AGC signal or load following, consider loads like crushers,
  - use a finer trading horizon, e.g. half hour to enable more participation from steel plants
- Cooperation with buildings, electric vehicles
- Energy hub with industrial loads, generators, ...
- Prediction of market prices

  ...