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Optimal Unit Commitment under Uncertainty in Electricity Markets

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With help from Brad Wagner at LRCA

PSERC

Opening remarks

- We describe a new way to think about Unit Commitment (UC) under uncertainty
  - We describe optimal commitment *strategies* not just optimal unit commitment
  - This talk is about concepts, not algorithms

With better technology, can we solve a better problem?

Our objectives

- To show that conventional UC does not lead to optimality under uncertainty
  - We use a trivially simple example
  - Optimality requires *strategies*, not schedules
- To outline a modified LR solution method
  - Options not considered include modifications to Mixed Integer Programming (MIP) methods

Stochastic Unit Commitment

- Consider using Lagrangian Relaxation (LR)
  - Since energy and reserve prices are *outputs* of UC, start with initial guesses of prices *and their probability distributions*
- Refine price estimates and *their probability distributions* until convergence is reached

Uncertainty matters: an example

- A 4-generator energy-only 2-scenario case
- Compare three UC methods

1. Deterministic commitment using expected values
2. Commitment based on Monte Carlo scenarios
3. Stochastic dispatch

The example

- Three future time periods t=1, 2, 3
- Four generators (next slide)
- Demand*: 146 MW, 181 MW, 146 MW
- Commitment decisions to be made at t=0
  - Find optimal commitment and dispatch *strategy* at t=0 to minimize expected total cost over all periods and all scenarios

(*) In this example the demand is certain

Example generator features

- Generator B, 100 MW, fixed schedule
- Generator G, **15**-40 MW, $33/MWh, startup $650, **minimum up time 2 periods**, initially offline
- Generator P, 60 MW, $50/MWh
- Generator W, 10 *or* 50 MW, negative $25/MWh*
  - W capability is **perfectly correlated**, i.e., it can produce up to either 10 MW or 50 MW across all periods
    - But we must wait for t=1 to find out…

(*) The capability of W is uncertain at t=0

1. Deterministic commitment

- Assume W produces 30 MW all 3 periods
- Dispatch is:
  - – Period 1: B=100, G=16, P=off, W=30. Price: $33
  - – Period 2: B=100, G=40, P=11, W=30. Price: $50
  - – Period 3: B=100, G=16, P=off, W=30. Price: $33
- Solution commits G at t=0 (**wrong**)

What happens when W=10 or when W=50?

2. Monte Carlo Scenarios

- For W =10:
  - G=[36,40,36], P=[0,31,0], W=[10,10,10], p=[$33, $50, $33]
- For W =50:
  - G=[0,0,0], P=[0,31,0], W=[46,50,46], p=[-$25, $50, -$25]
    - G does not start because its 2 hour minimum up time; losses in either period 1 or 3 negate profits in period 2
- Monte Carlo done this way is **incorrect** because for each scenario, *the future is certain*

B=100 all 3 periods, either scenario

3. Optimal Commitment ***Strategy***

- At t=0, **do not** commit G
- At t=1, commit G conditionally
  - **If W=10** at t=1, **commit G:** G=[0,40,36], W=[10, 10, 10], P=[36,31,0], p=[\$50, \$50, \$33]
  - **If W=50** at t=1, **do not commit G:** G=off, W=[46, 50, 46], P=[0,35,0], p=[-\$25, \$50, -\$25]

B=100 all 3 periods, either scenario

Deterministic

Period	B	G	P	W	D	$
1	100	16	0	30	146	33
2	100	40	11	30	181	50
3	100	16	0	30	146	33

Monte Carlo

1	100	**36**/0	**0**/0	10/46	146	**33**/-25
2	100	40/0	31/31	10/50	181	50/50
3	100	36/0	0/0	10/46	146	33/-25

Optimal Strategy

1	100	**0**/0	**36**/0	10/46	146	**50**/-25
2	100	40/0	31/31	10/50	181	50/50
3	100	36/0	0	10/46	146	33/-25

Correlation between periods need not be 100% for solution to be valid

Verifying the Solution

- Optimize G’s profits given two equally probable price forecasts at t=0:
  - Either price = [$50, $50, $33] or price = [-$25, $50, -$25]
- If G commits at t=0
  - G’s dispatch would be [40, 40, any] for scenario 1 and [15, 40, 0] for scenario 2
  - Profits = $710 for scenario 1 and -$840 for scenario 2; thus, expected profits are *negative*
  - Therefore it is not optimal for G to commit at t=0

Comments about the example

- The optimal commitment is a ***strategy*** **that is conditional on the state of the world**
- Many random scenarios can be handled (we use the trivially simple case of two scenarios)
  - Scenarios should consider demand uncertainty, correlation between output of wind between time periods, forced generator outages, etc.

Stochastic Unit Commitment: Possible Approaches

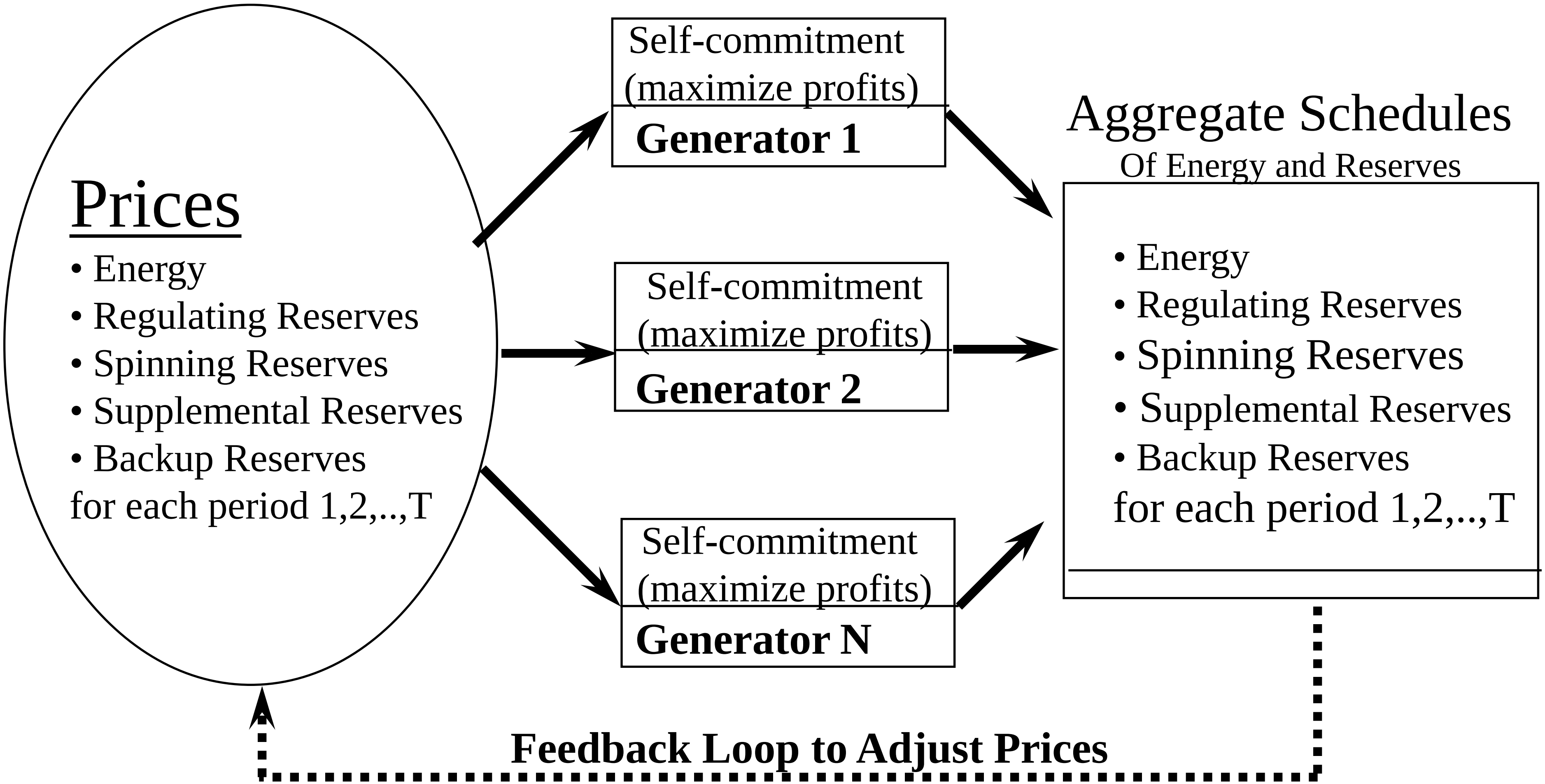
- Brute force Monte Carlo
- *Modified* Lagrangian Relaxation (LR)
  - Or perhaps *modified* Mixed Integer Programming (MIP) – not explored here

Stochastic Unit Commitment by LR

- We suggest an adaptation of LR
- The optimal solution is characterized by prices and their ***probability distribution***, and by generator commitment and ***dispatch strategy*** for each
- At the optimum:
  - *Expected* total costs (over all time periods and uncertainty scenarios) are minimized
  - For each generator, *expected* profits are maximized

Traditional Lagrangian Relaxation

Maximize profits over T periods



Prices

- Energy
- Regulating Reserves
- Spinning Reserves
- Supplemental Reserves
- Backup Reserves

for each period 1,2,..,T

Self-commitment (maximize profits)
Generator 1

Self-commitment (maximize profits)
Generator 2

Self-commitment (maximize profits)
Generator N

Aggregate Schedules
Of Energy and Reserves

- Energy
- Regulating Reserves
- Spinning Reserves
- Supplemental Reserves
- Backup Reserves

for each period 1,2,..,T

Feedback Loop to Adjust Prices

(ensure that dispatch satisfies system requirements)

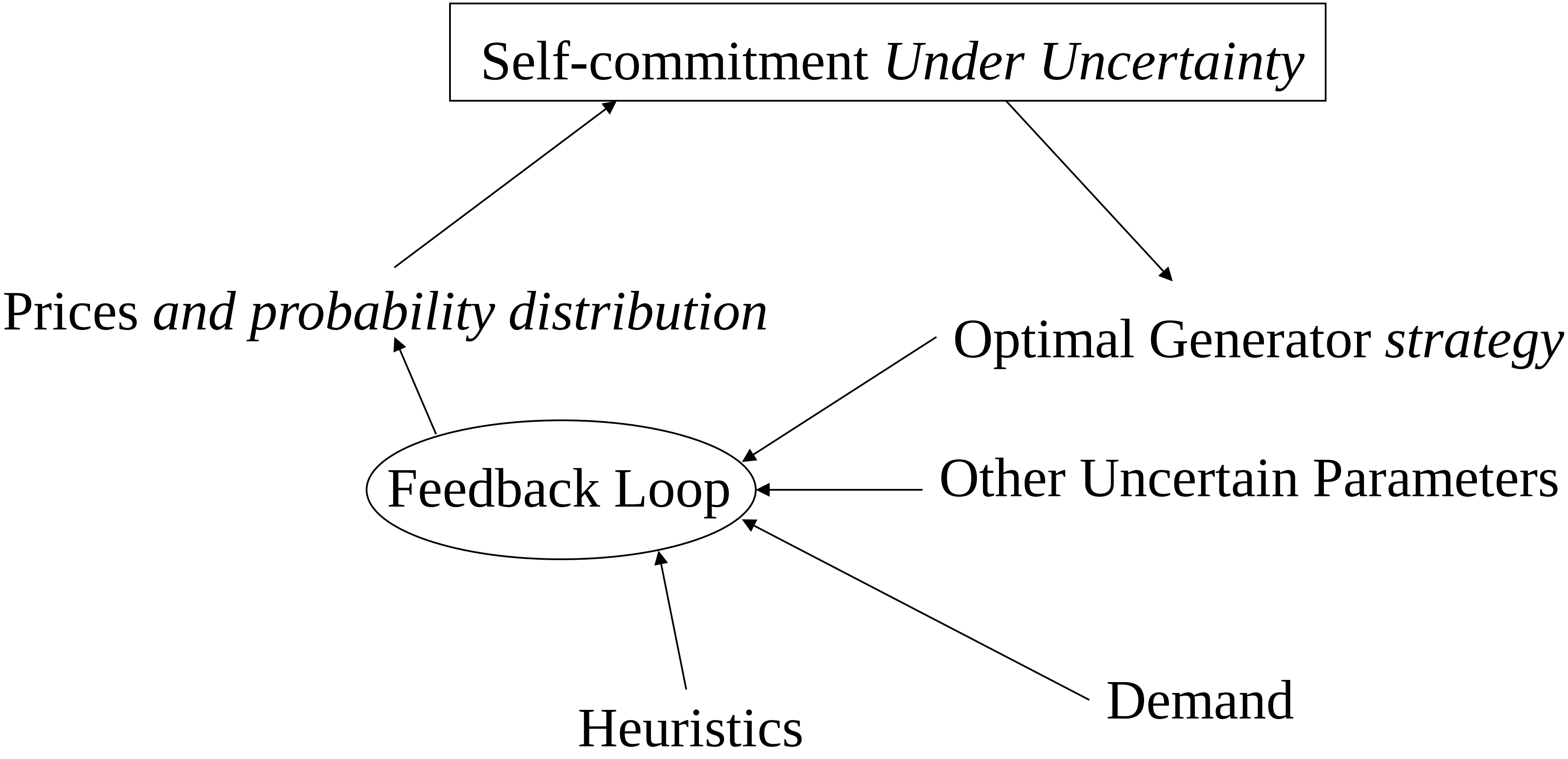
Traditional LR (step 1)

- Use **prices** as intermediate variables to decouple commitment among generators
  - Given prices of energy and reserves, produce a profit-maximizing schedule for any generator using backward DP
    - Find profit-maximizing schedules for each period and for each generator
      - This yields generation schedules for each period

Traditional LR (step 2)

- If aggregate schedules from step 1 differ from energy and reserve requirements in any period, adjust prices and repeat step 1
  - The price is adjusted through gradient search
  - Caveats:
    - Convergence can be unstable
    - Dual solution may not be feasible
    - Near degeneracy of solutions
    - Issues often handled by heuristics during the final iterations

LR *under uncertainty*



Self-commitment *Under Uncertainty*

Prices *and probability distribution*

Optimal Generator *strategy*

Feedback Loop

Other Uncertain Parameters

Heuristics

Demand

The proposed *modified* LR

- Part 1: Self-commitment
  - Self commitment must consider uncertainty
    - “Self-commitment” can be done by the system operator
  - The result is a *strategy*, not a fixed schedule
- Part 2: Feedback Loop
  - Prices are not just prices, they are price *distributions*
  - They are adjusted based on mismatch between aggregate schedules and aggregate demand, and based on uncertainty parameters

Optimal self-commitment strategies

- There is an *optimal strategy* that a generator can follow to optimize its expected profits
  - A “*self-commitment*” *optimal* ***strategy*** differs from a commitment based on certainty of prices
- The problem is solved using nested backward dynamic programming

The problem can be solved by the ISO on behalf of each generator
(i.e, “self-commitment” is a bit of a misnomer)

Generator-level decision issues

- Prices are uncertain
- How much to allocate to each market?
  - *Energy or various types of reserves*
- Operational constraints
- Obtain estimates of profits and losses

Cost Characteristics

- Generator costs can include:
  - Incremental or marginal costs
  - Startup/shutdown costs
  - No-load costs
  - Ramping costs
- Cost may be non-convex because of:
  - Startup and shutdown costs
  - “Valve points”
  - Declining marginal costs

Generator Operational Constraints

- MW limits on energy and reserves
- Sum of energy and reserve MWs limits
- Inter-temporal constraints
  - Minimum up/down times
  - Startup delays
  - Multi-period emissions or energy constraints
  - Ramping rate limits

Generator-level decisions

- Generators decisions must consider profits over many periods
  - Are *expected revenues* > *expected costs*?
- For each period, decisions include:
  - Startup/Shutdown?
  - Ramp up/down next hour?
  - Offer reserves or energy?
    - Or some of each?

Reasons for price variability

- Uncertainty in demand
  - Weather and non-weather related
- Generation output uncertainty
  - Forced outages
  - Wind uncertainty
- Transmission outages
  - Contingency constraints and congestion

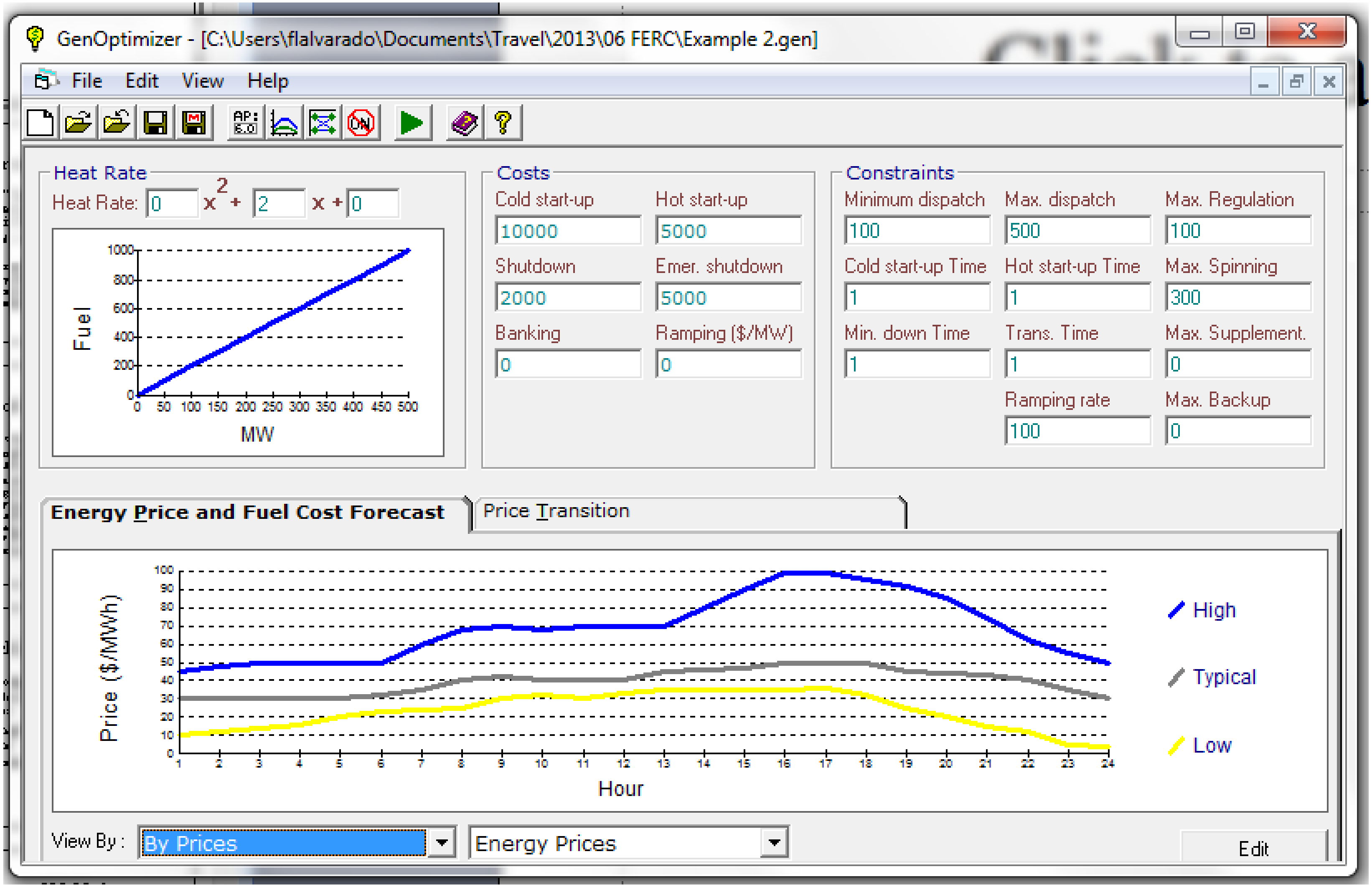
Handling Price Uncertainty

- Use discrete price states (*High/Medium/Low)*
- Determining optimal commitment strategy is similar to determining when to exercise an option
  - When to commit, when to sell reserves, etc.
- Price correlation issues:
  - Are prices correlated between time periods?
  - Are prices correlated between markets?

Locational factors

- Every generator sees a unique price distribution for energy (and reserves) as a result of congestion and losses
- Optimal commitment on a generator-by-generator basis optimizes every generator’s value to the system

Sample energy costs and prices



Heat Rate

Heat Rate: 0 x^2 + 2 x + 0

Costs

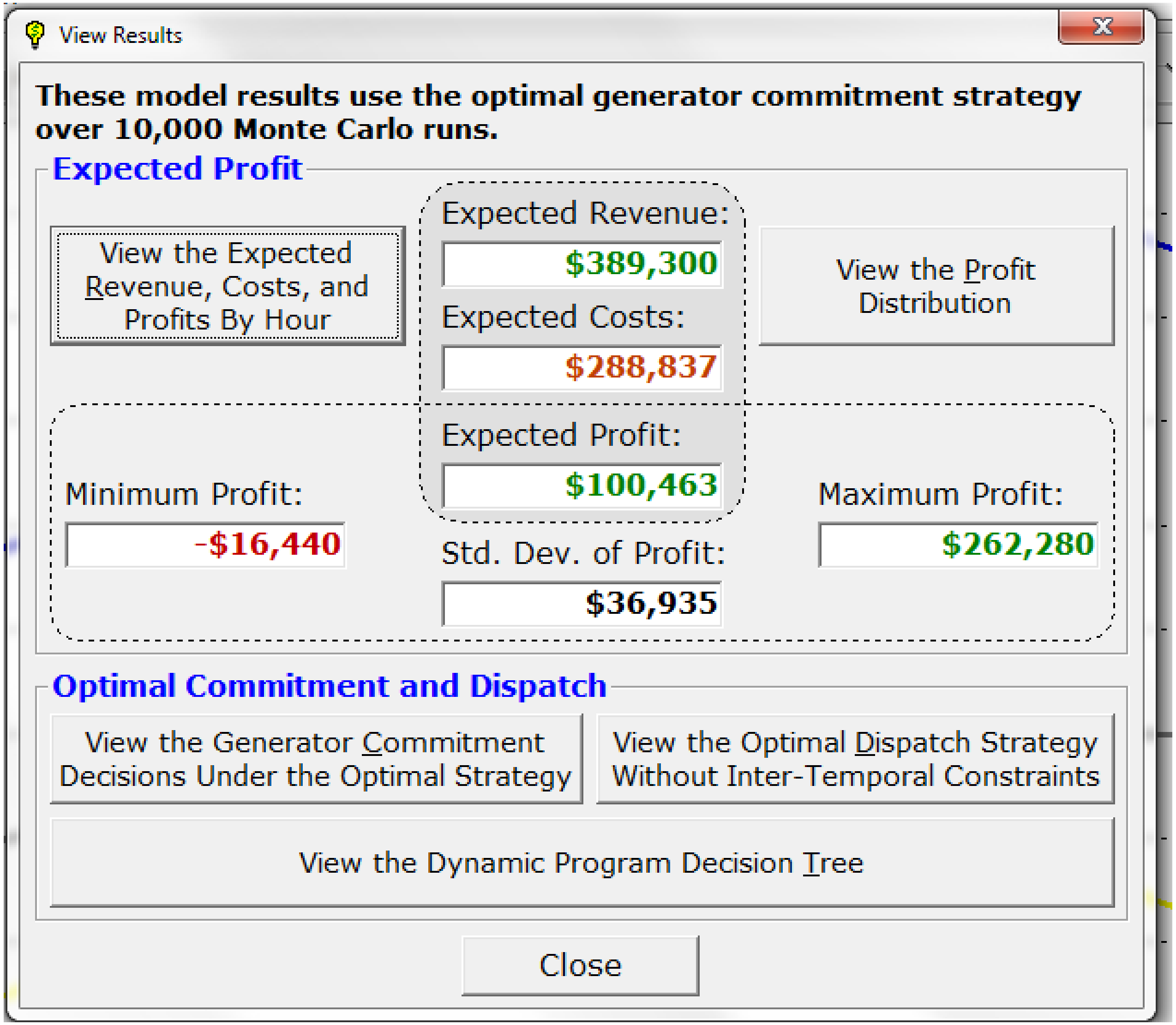
Cold start-up: 10000
Hot start-up: 5000
Shutdown: 2000
Emer. shutdown: 5000
Banking: 0
Ramping ($/MW): 0

Constraints

Minimum dispatch: 100
Max. dispatch: 500
Max. Regulation: 100
Cold start-up Time: 1
Hot start-up Time: 1
Max. Spinning: 300
Min. down Time: 1
Trans. Time: 1
Max. Supplement.: 0
Ramping rate: 100
Max. Backup: 0

View By: By Prices
Energy Prices

Results summary



View Results

These model results use the optimal generator commitment strategy over 10,000 Monte Carlo runs.

Expected Profit

Expected Revenue: $389,300

Expected Costs: $288,837

Expected Profit: $100,463

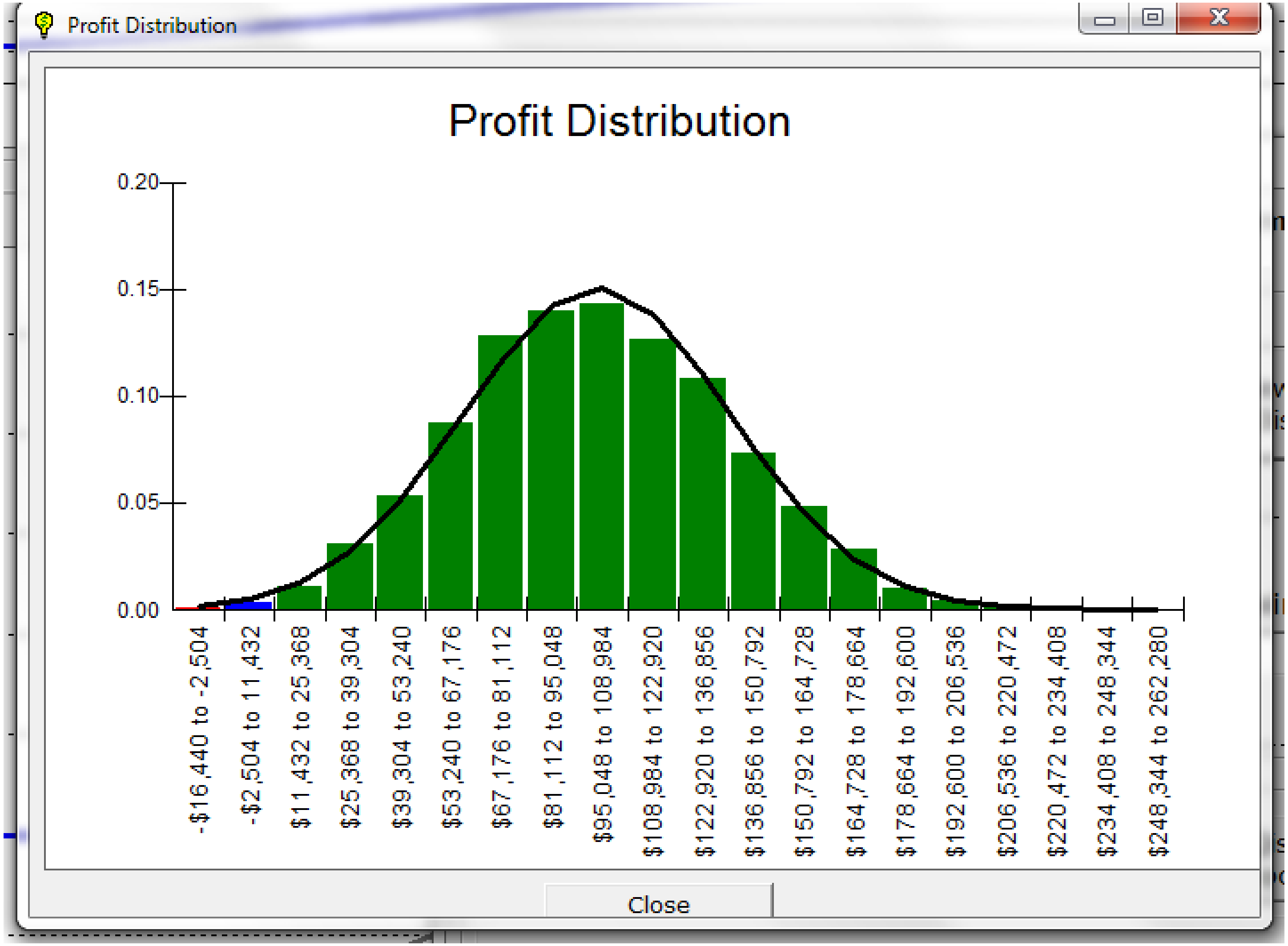
Minimum Profit: -$16,440

Std. Dev. of Profit: $36,935

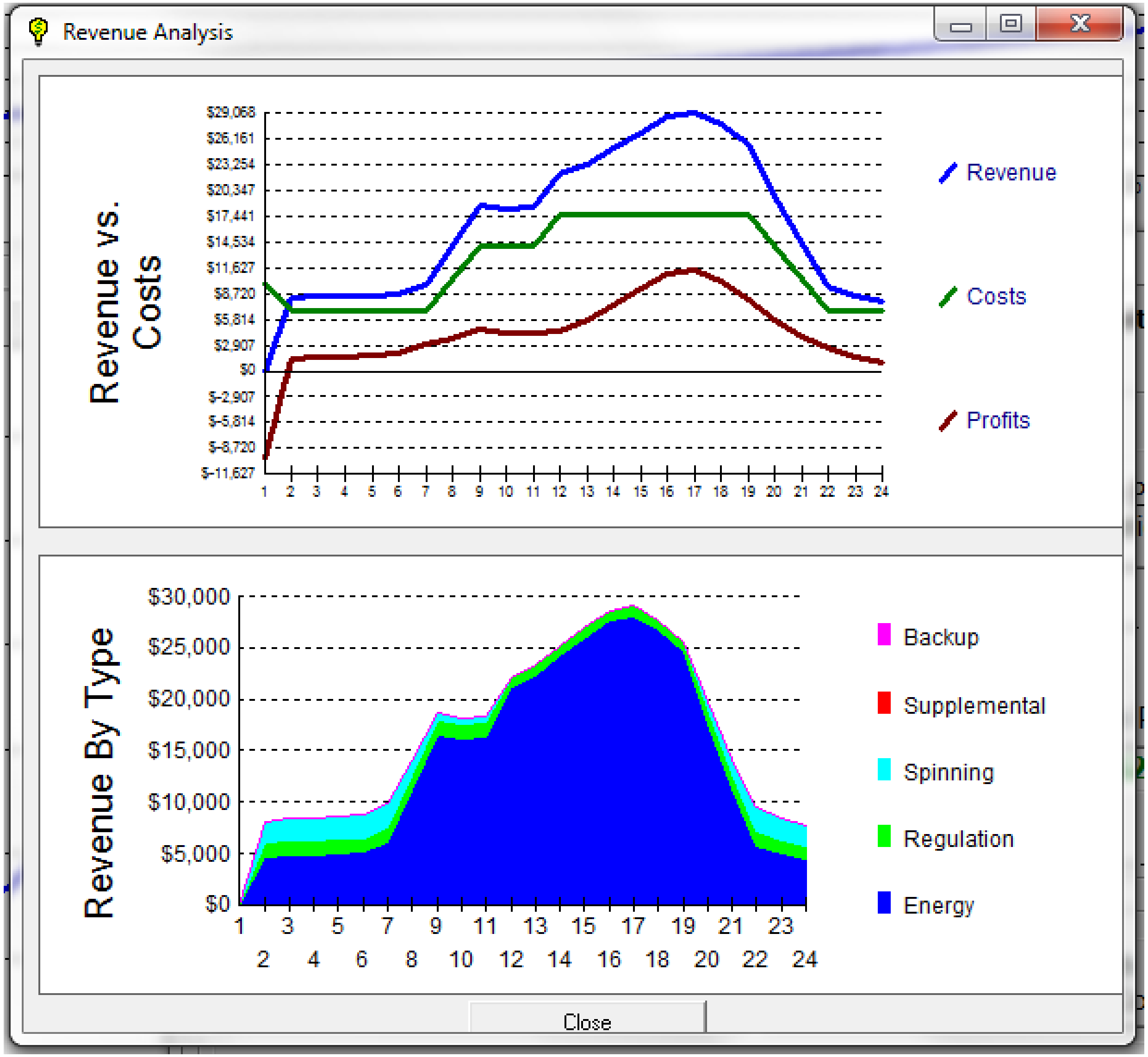
Maximum Profit: $262,280

Optimal Commitment and Dispatch

Profit distribution



Expected profits and costs by hour



For more details…

- See “Optimal Bidding Strategy Under Uncertain Energy and Reserve Prices”, PSERC Publication 03-05, April 2003
  - Find optimal self-commitment *strategy* under uncertainty
  - Is “implemented” by GenOptimizer, a program developed by LRCA
    - GenOptimizer can be used for transmission planning, bidding strategies, generator siting analysis, etc.
- See also Rajaraman, R. and B. Wagner. “Understanding Generator Optionality: How the Tools of Stock Brokers and Poker Players Are Shaping the World of Generator Self-Commitment.” *The Electricity Journal* 17(9):68-77, Nov. 2004

Feedback Loop Description

- Step 0: Assume energy and reserve price distributions
- Step 1: Get optimal UC strategies for each generator
  - Perfect for parallel computation
- Step 2: Aggregate schedules and compare to energy and reserves system requirements
  - Adjust prices based on mismatch between generation and requirements
    - Use Monte Carlo applied to optimal commitment strategies
- Go to Step 1 if not converged

Heuristics needed to simplify computations (research required)

Impact on ISO Markets

- Most ISOs run one day-ahead UC per day
- Replace DA UC by a dynamic, rolling, 24-hour look-ahead stochastic UC run each hour
- Update commitment decisions every hour
  - This will result in changes in the DA market, but the market will produce better results

Parting comments

- We redefine Unit Commitment from "create a *schedule*" to "create a *strategy*"
  - We suggest using a rolling hourly 24-hour UC
- We suggest a *modified* LR method to handle price uncertainty
  - Other possibilities include modified MIP
- The approach is optimal for each generator
- It is well suited for parallel computation

GenOptimizer*: Optimal self-commitment under uncertainty

- It implements optimal self-commitment:
  - It finds profit maximizing strategies
  - It can assist in finding optimal bidding strategies
  - It can help assess transmission needs
  - It can help value generation (including wind)
- It is educational and informative

(*) Developed by Laurits R. Christensen Associates.
For more information contact Brad Wagner at LRCA (brad@caenergy.com)

Uses of GenOptimizer

- For optimal self-dispatch under uncertainty
- For transmission planning assessment
- For generator bidding strategy optimization
  - In disputes about market power behavior
- For generator valuation and siting analysis
- As part of an integrated UC under uncertainty as proposed in this talk

GenOptimizer Inputs

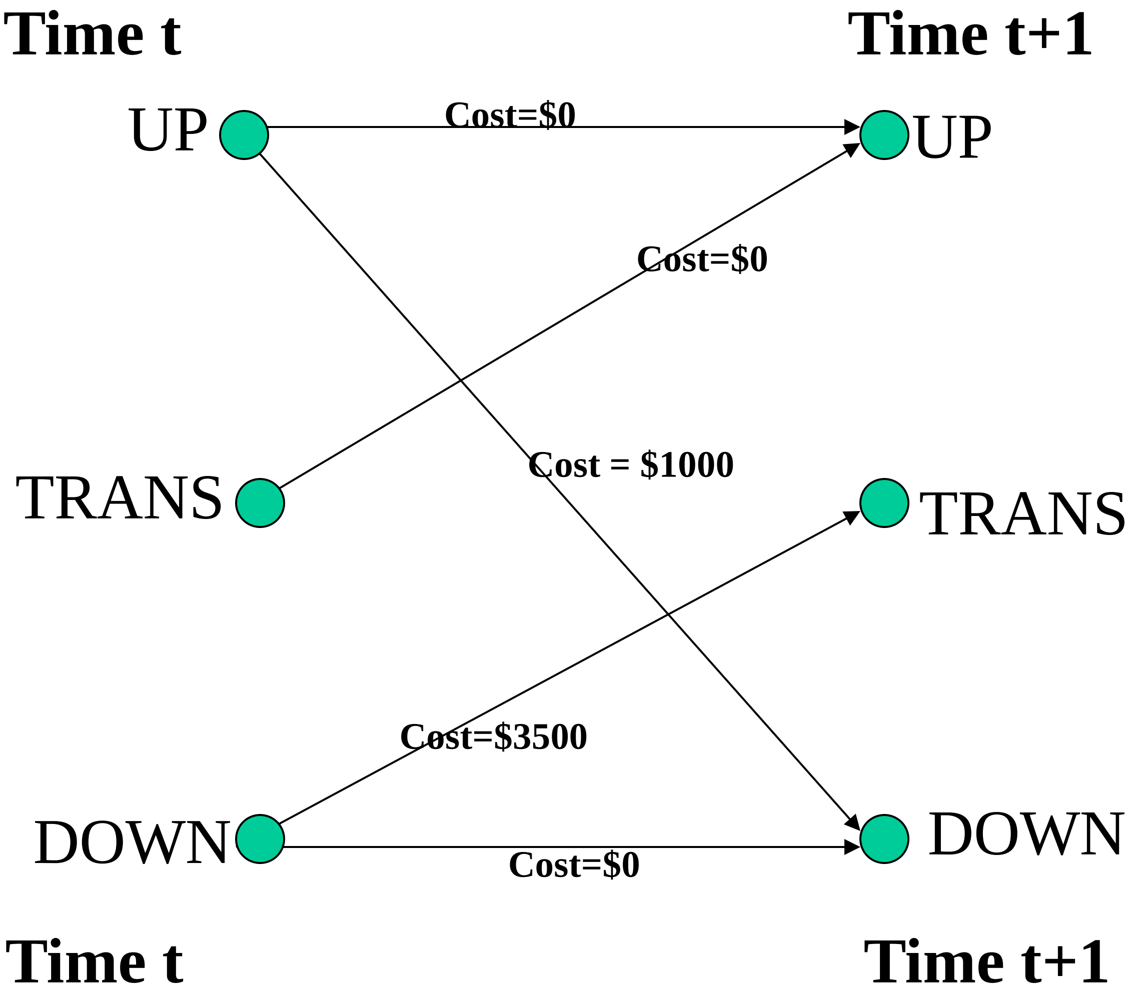
- Energy and reserve price forecasts
- Price volatilities
- Fuel costs
- Generator heat rate
- Minimum and maximum energy dispatch constraints
- Maximum reserve dispatch constraints
- Likelihood that offered reserve services will be called
- Start up time of a cold generator vs. a hot generator
- Minimum down time of a generator

GenOptimizer Inputs (cont.)

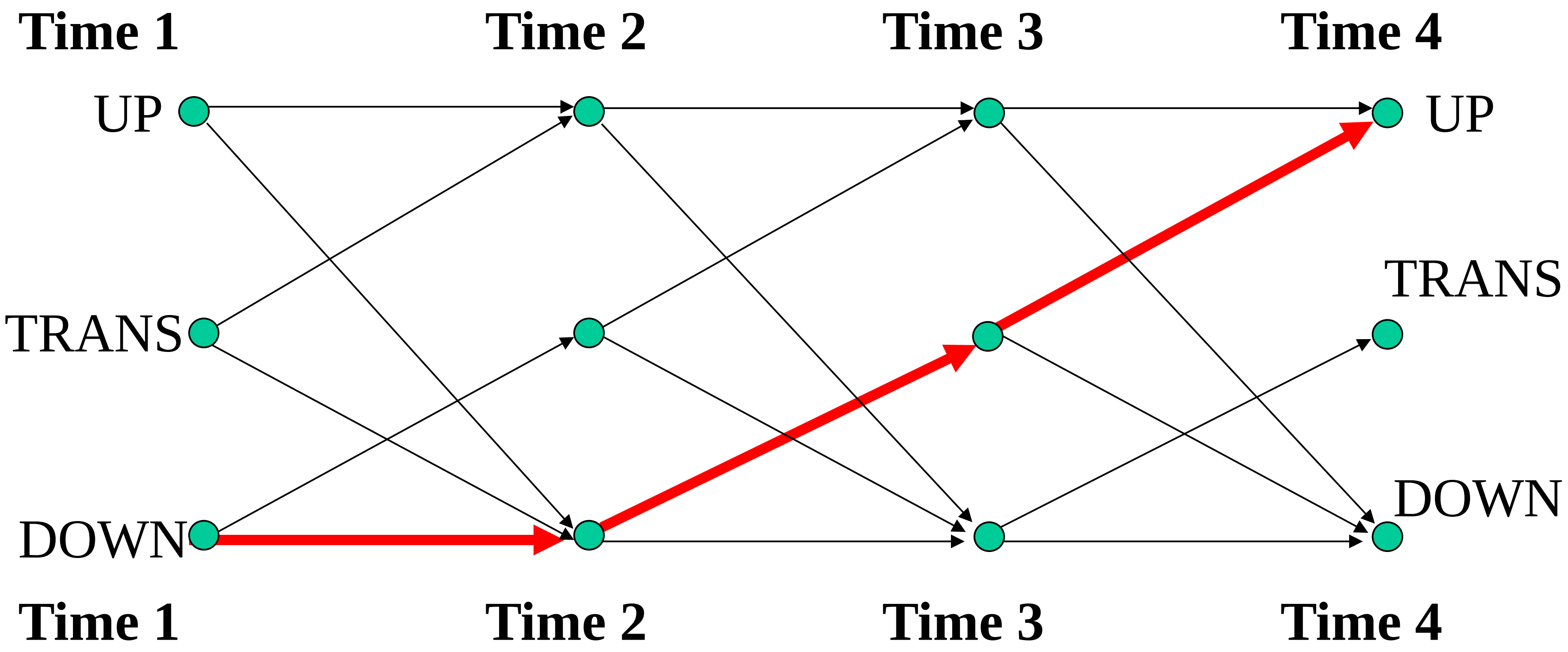
- Time it takes for a hot generator to become cold
- Ramping rate of the generator
- Cost to start a cold generator vs. a hot generator
- Cost to shut down the generator from a low dispatch vs. a high dispatch
- Banking costs
- No-load costs
- Ramping costs
- Planned generator outages and must-run conditions

Or just about anything an individual generator could care about

How to Model State Transitions

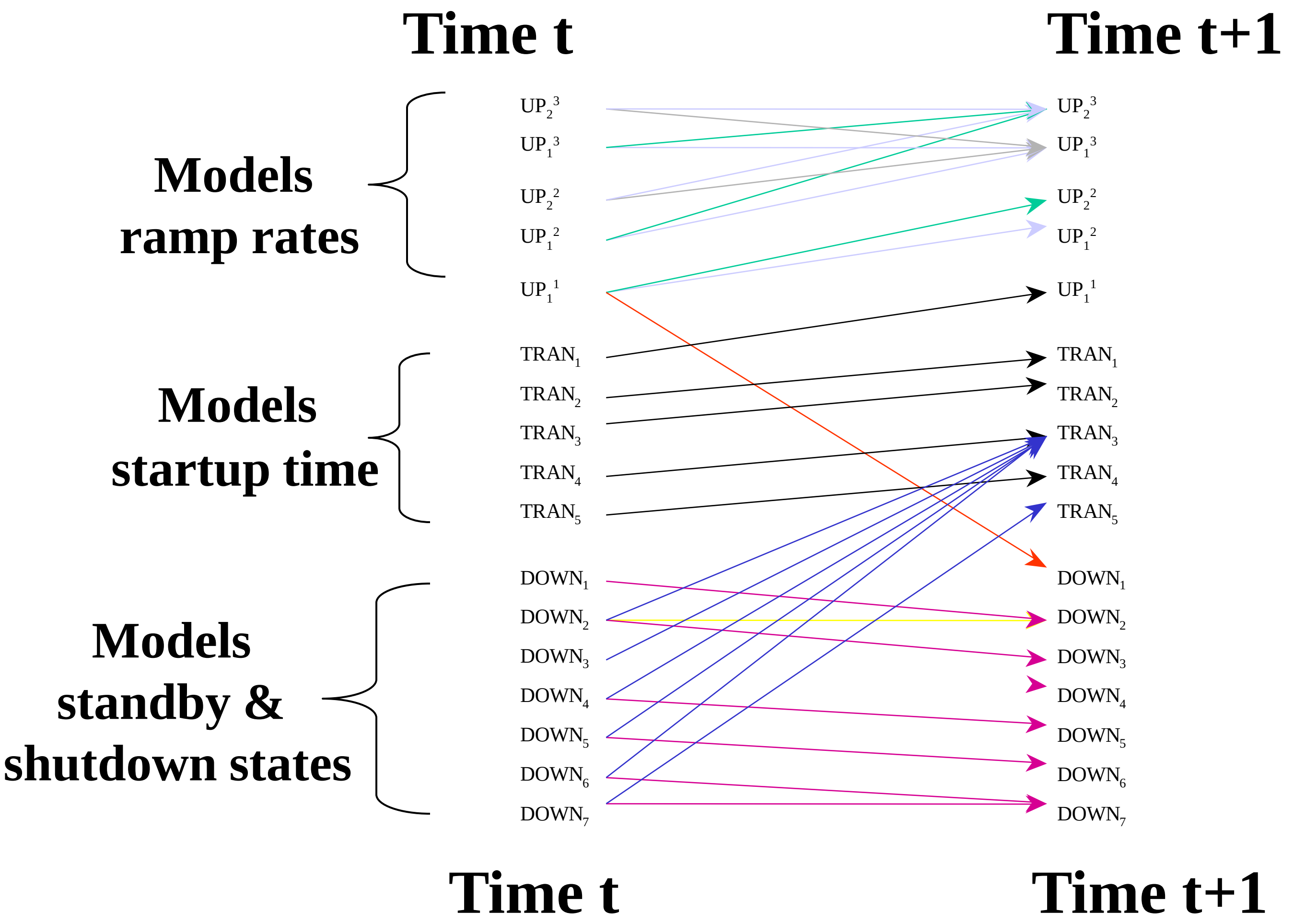


Feasible State Transitions



Use *Backward DP* to solve self-commitment problem

How to model ramp rates, startup times and inter-temporal constraints



Time t **Time t+1**

Models ramp rates

Models startup time

Models standby & shutdown states

UP_2^3
UP_1^3
UP_2^2
UP_1^2
UP_1^1
TRAN_1
TRAN_2
TRAN_3
TRAN_4
TRAN_5
DOWN_1
DOWN_2
DOWN_3
DOWN_4
DOWN_5
DOWN_6
DOWN_7

UP_2^3
UP_1^3
UP_2^2
UP_1^2
UP_1^1
TRAN_1
TRAN_2
TRAN_3
TRAN_4
TRAN_5
DOWN_1
DOWN_2
DOWN_3
DOWN_4
DOWN_5
DOWN_6
DOWN_7

Time t **Time t+1**

GenOptimizer Execution

- Backward Dynamic Programming determines the optimal strategy in every time period, generator dispatch state, and price level
  - Considers price uncertainty and operational constraints
- Monte Carlo is used to evaluate the performance of the commitment strategy under price volatility.
- Finds the optimal energy and reserve dispatches for given price levels

GenOptimizer Outputs

- Expected revenue, costs, and profit by hour for energy and reserve services
  - Standard deviation of expected profit
- Distribution of profits
  - Minimum and maximum profit achieved over a set of Monte-Carlo runs
- Analysis of commitment and optimal dispatch strategies

Time permitting, we will do a short demonstration of GenOptimizer