ILLINOIS INSTITUTE OF TECHNOLOGY

Cost of Reliability Analysis Based on Stochastic Unit Commitment

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2009

Outline

- Introduction to Stochastic SCUC
- Stochastic Simulation
- Stochastic Midterm SCUC Model
- Reliability of Midterm SCUC Problem
- Reliability Assessment of Power Systems with Optimal Midterm Hydro and Natural Gas Allocations
- Conclusions

Introduction

- Midterm SCUC
  - Coordination between fuel allocation, emission allowance and natural resources with midterm generation scheduling
  - A wider range of options to manage the security in short-term and real-time power system operations
- Stochastic Techniques for SCUC
  - Stochastic techniques are used to ensure that the midterm SCUC operation can withstand unpredictable events while taking constraints into consideration
  - Uncertainty factors considered in the midterm power system operation
    - Random outages of power system components
    - Load forecast errors
    - Natural resources (water, wind, solar) availabilities

Simulation of Stochastic Characteristics

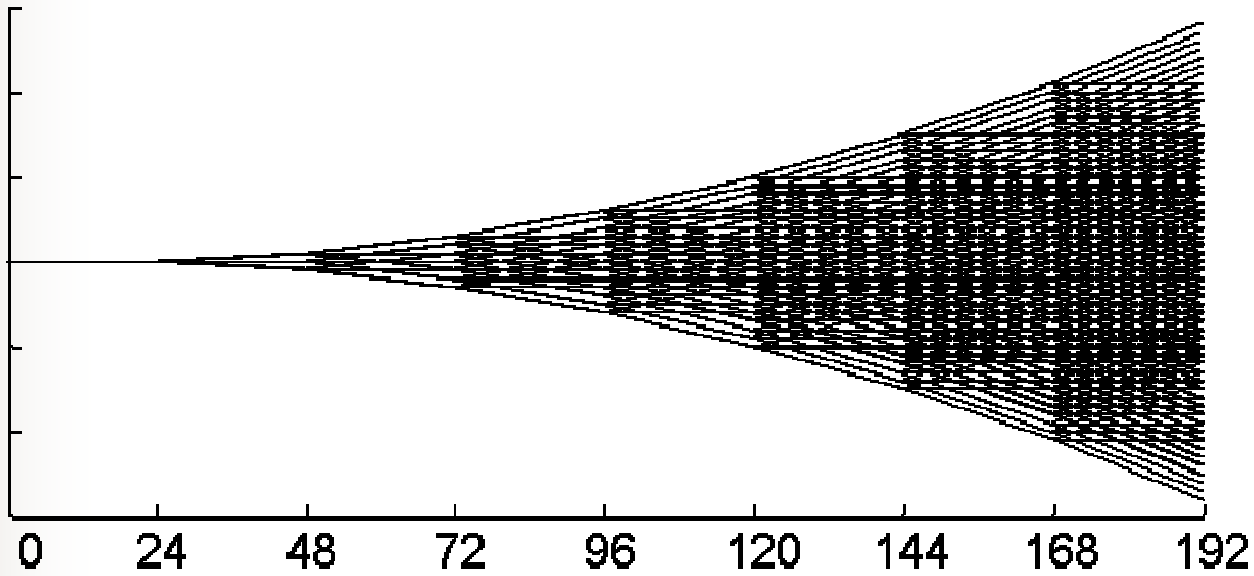
- Random failures of power plants and outages of transmission lines
  - Specify the initial state of each component. Simulate the duration of each component residing in its present state by a two-state continuous-time Markov model based on failure and repair rates
- Midterm load forecast errors
  - Load forecast errors are described by a normal distribution. The distribution is divided into a discrete number of intervals. The load representing the interval mid-point is assigned probability for that interval.
- Natural water inflow to a reservoir
  - It follows a discrete Markov chain, which is independent of inflows to other reservoirs, thus the spatially independent log-normal random variable is used to simulate the natural water inflow which is correlated in time with a first-order lag.

Stochastic SCUC Problem Formulation

- Objective
  - Minimize the social cost, including operation cost (i.e. the production cost, startup and shutdown costs of individual units) and possible load shedding costs in the entire midterm horizon.
- Constraints sets
  - System power balance and reserve constraints.
  - Individual generator constraints including ramping up/down rate limits, minimum on/off time limits, generation unit capacity limits, fuel/emission constraints for groups of units, etc .
  - Transmission constraints, including dc network security constraints and phase shifter angles limits.
  - Scenario bundle constraints

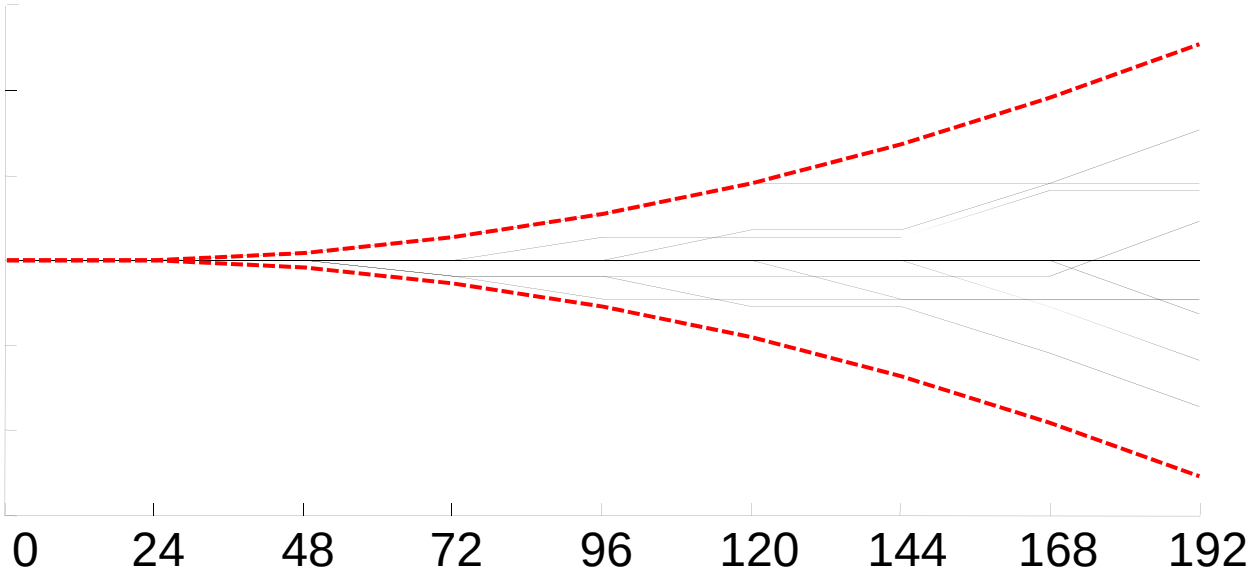
Stochastic Midterm SCUC

- Monte Carlo method is adopted to generate a set of scenarios, each representing random outages and load forecast errors in the midterm power system operation.
- Scenario reduction and scenario aggregation techniques are used to build an easy-to-solve stochastic midterm SCUC model.
- Midterm fuel allocation and emission allowance are considered, and DC power flow is included in the model.
- Lagrangian relaxation is applied to decompose coupling constraints among scenarios. Dual decomposition is used as a price-based coordination approach to solve midterm fuel allocation and emission allowance constraints for each scenario.



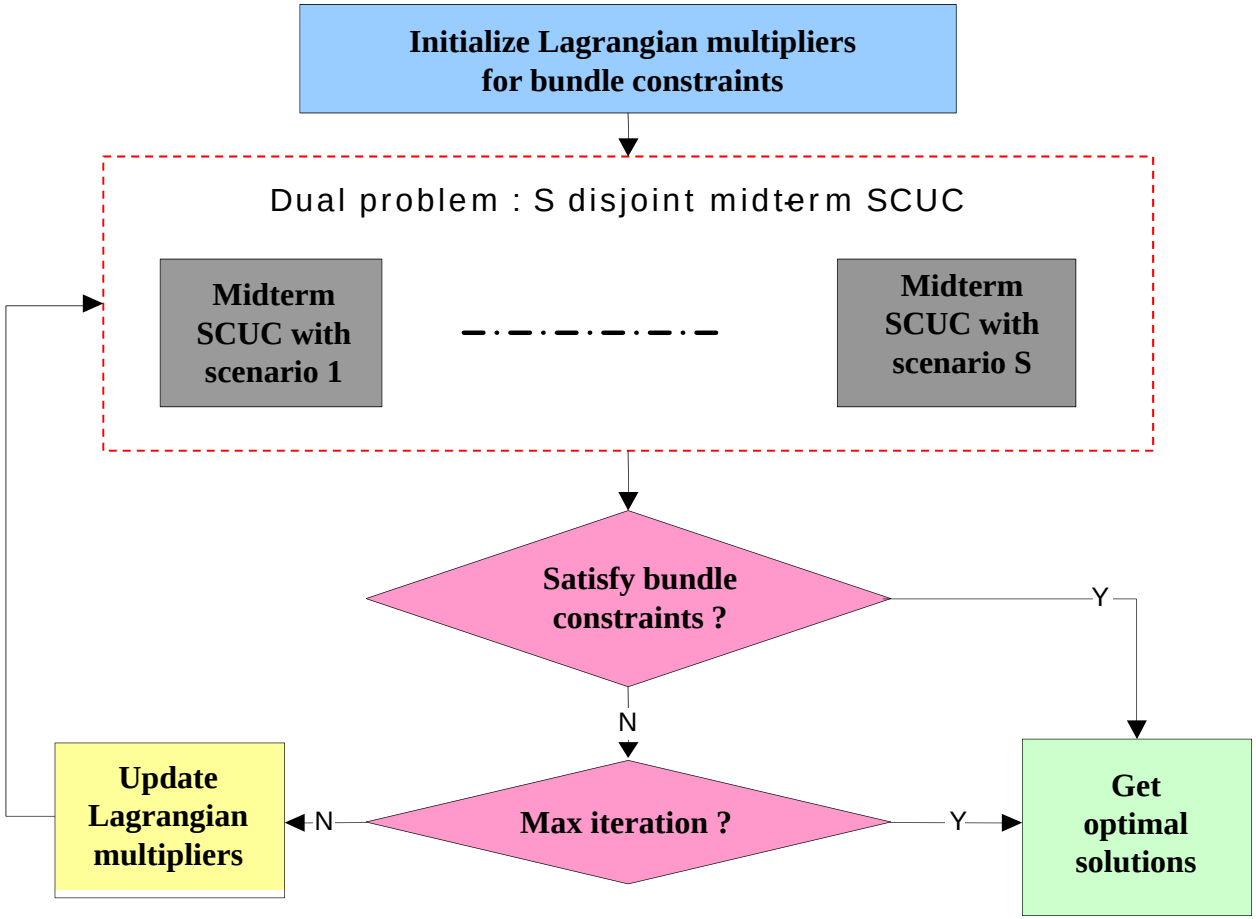
3^7 scenarios generated based on MC

After scenario reduction ten scenarios left

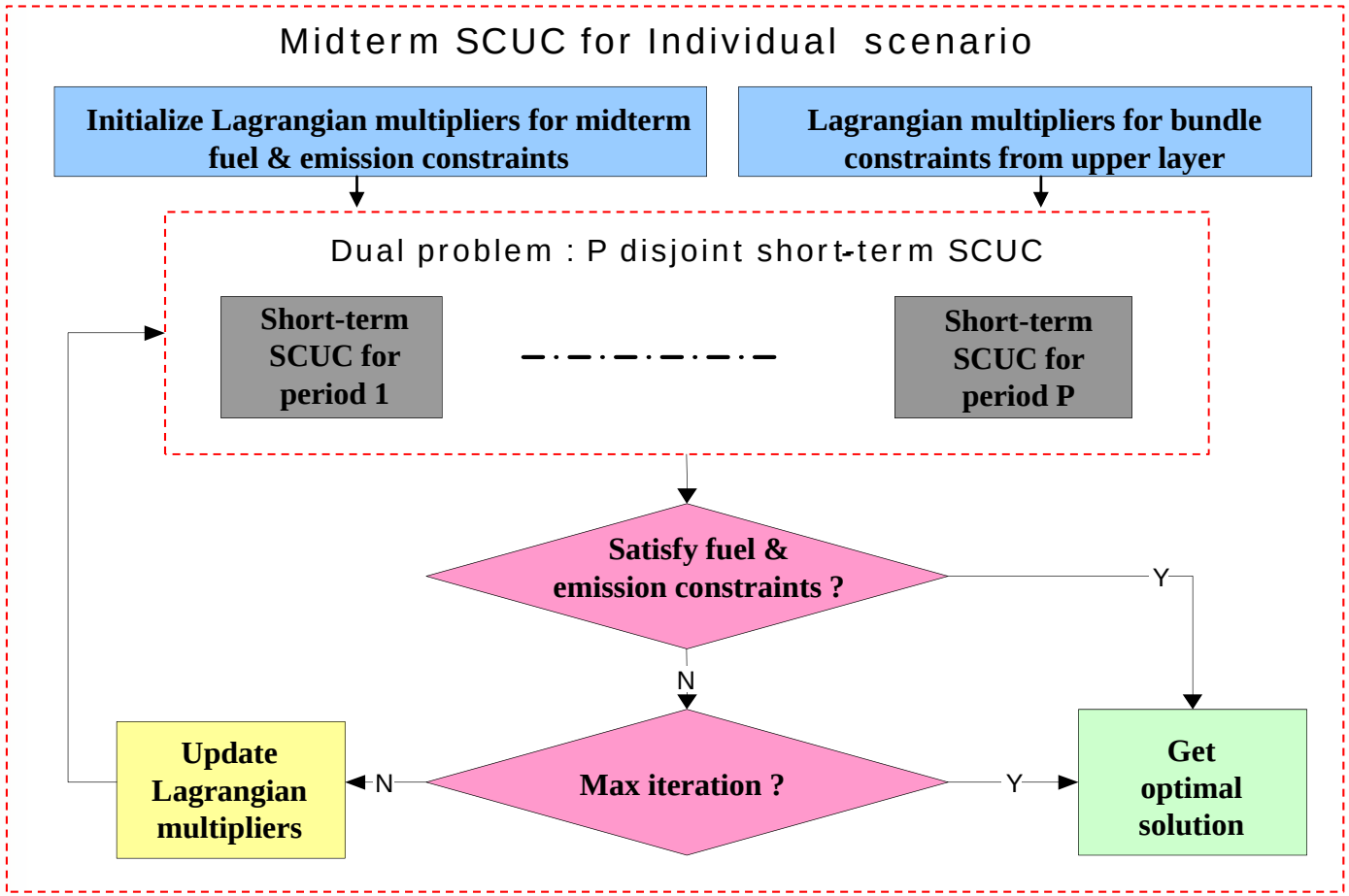


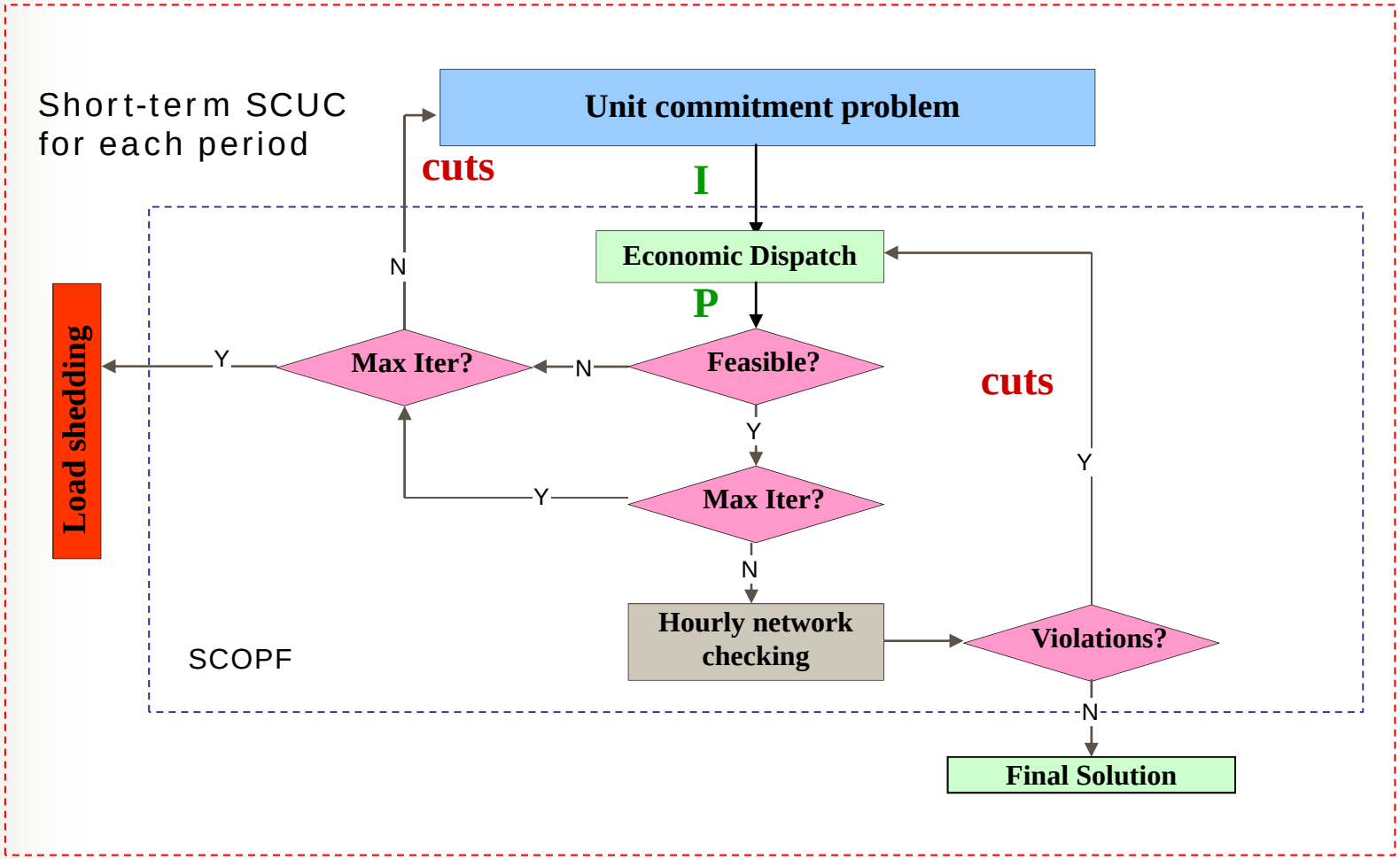
Decomposition Methodology

- Decomposition of bundle constraints among scenarios

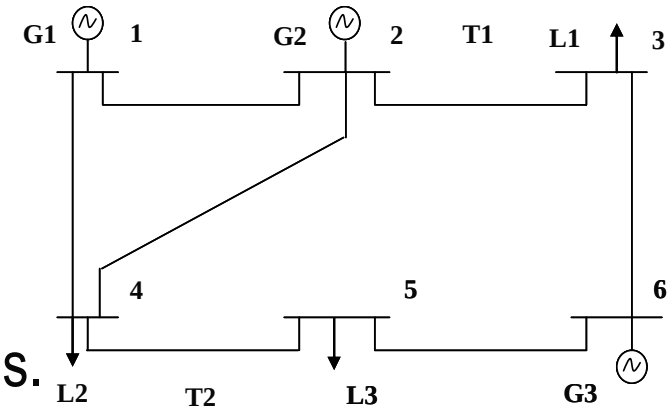


- Decomposition of Midterm fuel and emission constraints



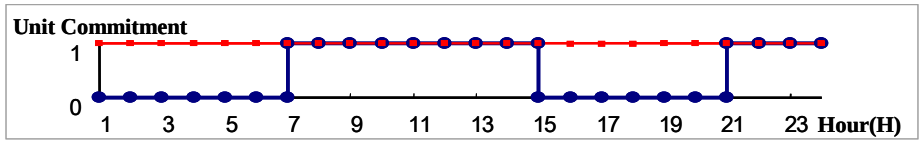

Short-term SCUC
for each period
Unit commitment problem
cuts
I
Economic Dispatch
P
N
Load shedding
Y
Max Iter?
N
Feasible?
cuts
Y
Y
Max Iter?
Y
N
Hourly network
checking
Violations?
SCOPF
N
Final Solution

Six-bus Test System

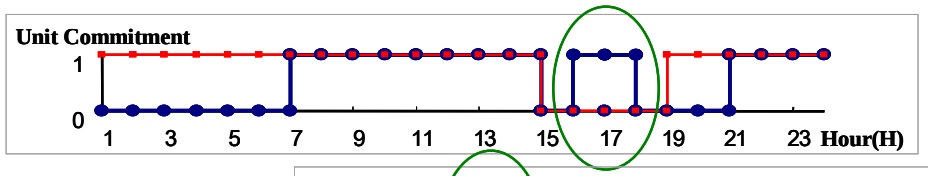


- Case 1: Base case without any uncertainties.
- Case 2: Consider random generator and transmission line outages, system load is the same as base case.
- Case 3: Consider random generator and transmission line outages, as well as load forecast errors.

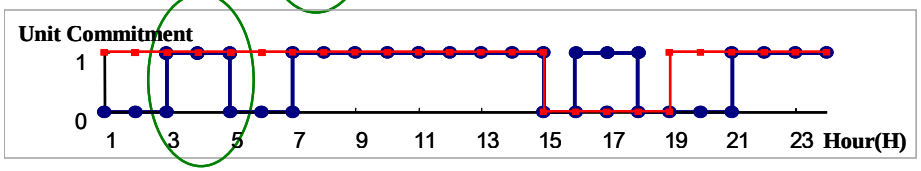
Case 1



Case 2



Case 3



Expensive G3 Inexpensive G1

Definition of Reliability

- Adequacy
  - The ability to supply consumers' power requirements at all time
  - Sufficient generation and transmission resources are available to meet projected needs plus reserves for contingencies

- Security
  - The ability of withstanding a normal operation without sudden disturbances
  - The ability to remain intact and supply the power energy to end users uninterruptedly after the occurrence of outages or equipment failures

Reliability and Economics

- Power systems are forced to operate at their margins for maximizing the economics.
- In order to ensure reliability, components outages and demand fluctuations are to be considered in power systems.
- A trade-off between reliability and economics
  - Supply individual loads and satisfy power system constraints even in emergency conditions
  - Least-cost supply of electric power while enforcing reliability constraints

Applications of SCUC to Reliability

- Instead of applying N-1 or other deterministic contingency criteria, we apply the Monte Carlo method to simulate possible contingencies in stochastic SCUC.

- With the introduction of LOLE and EENS indices in the stochastic SCUC model, we determine implicitly the probabilistic spinning/non-spinning reserves as a tradeoff between reliability and economics.

- A scenario-based technique is adopted to control a goodness-of-fit of approximation between computation time and solution accuracy.

Reliability Formulation

- Objective Function

$$\min \sum_{s=1}^{S} P_s \sum_{p=1}^{NP} \sum_{t=1}^{NT} \{ \sum_{i=1}^{NG} [F_{c,itp}(P_{itp}^{s} * I_{itp}^{s}) + SU_{itp}^{s} + SD_{itp}^{s}] + \sum_{b=1}^{NB} C_{b,tp}^{s} * LS_{b,tp}^{s} \}$$

- Constraints
  - UC constraints
    - Real power generation limits
    - Ramping un / down constraints
    - Minimum on / off time constraints
    - Fuel constraints for group of units
    - Emission constraints for group of units

Reliability Formulation (Cont'd)

- Network security constraints
  - DC power flow
  - Transmission flow constraints

- Bundle constraints for scenarios
  - If two scenarios are indistinguishable on the basis of information available at time τ, the unit commitment decision rendered for the two scenarios must be identical from beginning to time τ.

- Reliability constraints

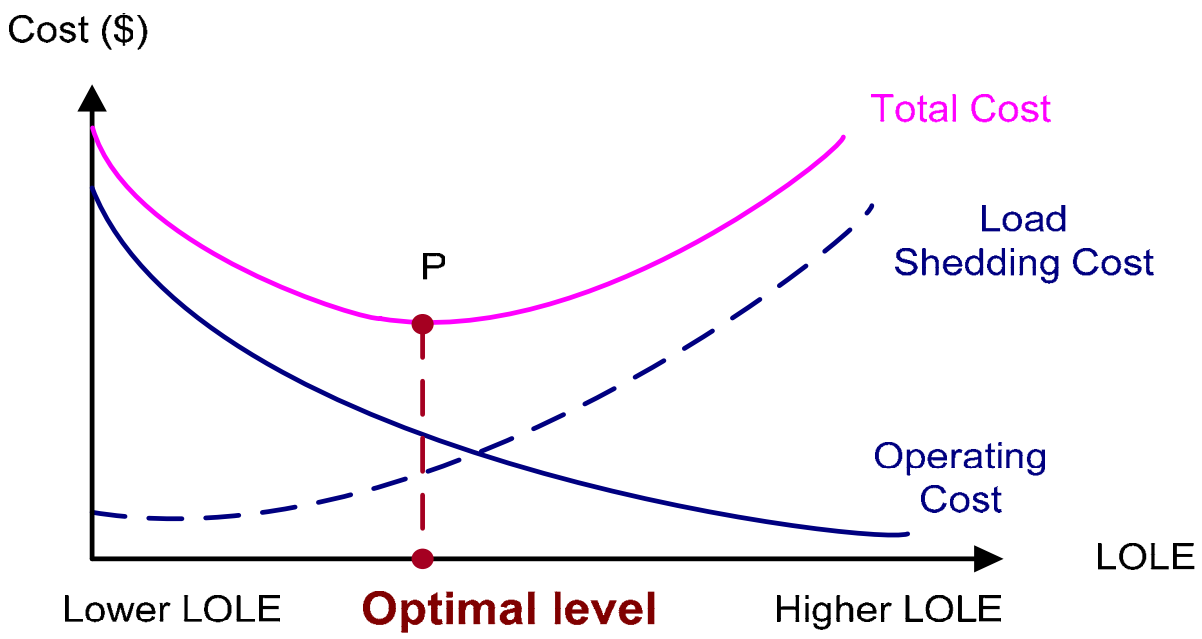
$$0 \le LS_{b,tp}^{s} - (P_{b,tp}^{s} - \sum_{i \in B_b} P_{i,tp}^{s} - \sum_{l \in L_b} PL_{l,tp}^{s}) \le M \cdot (1 - LSIDX_{tp}^{s})$$

$$0 \le LS_{b,tp}^{s} \le M \cdot LSIDX_{tp}^{s}$$

$$LS_{b}^{s} = \sum_{p=1}^{NP} \sum_{t=1}^{NT} LS_{b,tp}^{s} \qquad \forall t, \forall p, \forall s \quad LSIDX_{tp}^{s} \in \{0,1\}$$

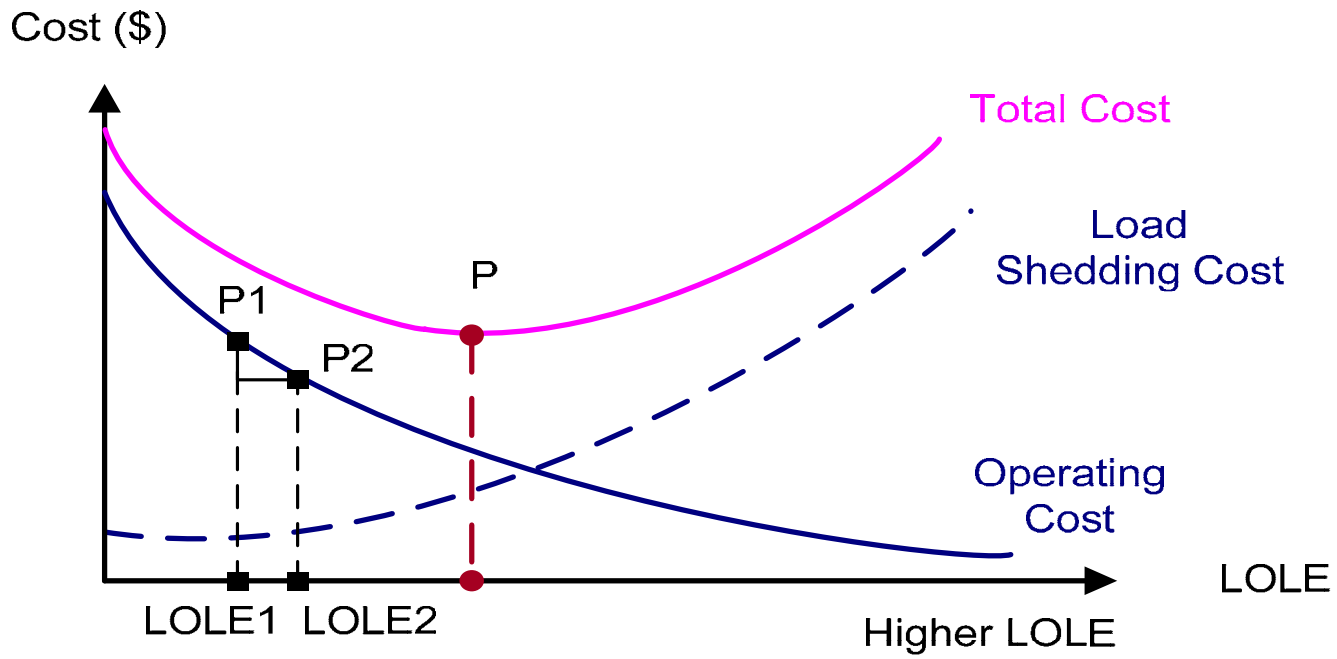
$$LOLE^{s} = \frac{\sum_{p=1}^{NP} \sum_{t=1}^{NT} LSIDX_{tp}^{s}}{NT * NP} \le LOLE_{fix} \qquad \forall s$$

Variation of Cost as a Function of Reliability



The result represents a minimum total cost while satisfying a certain level of reliability.

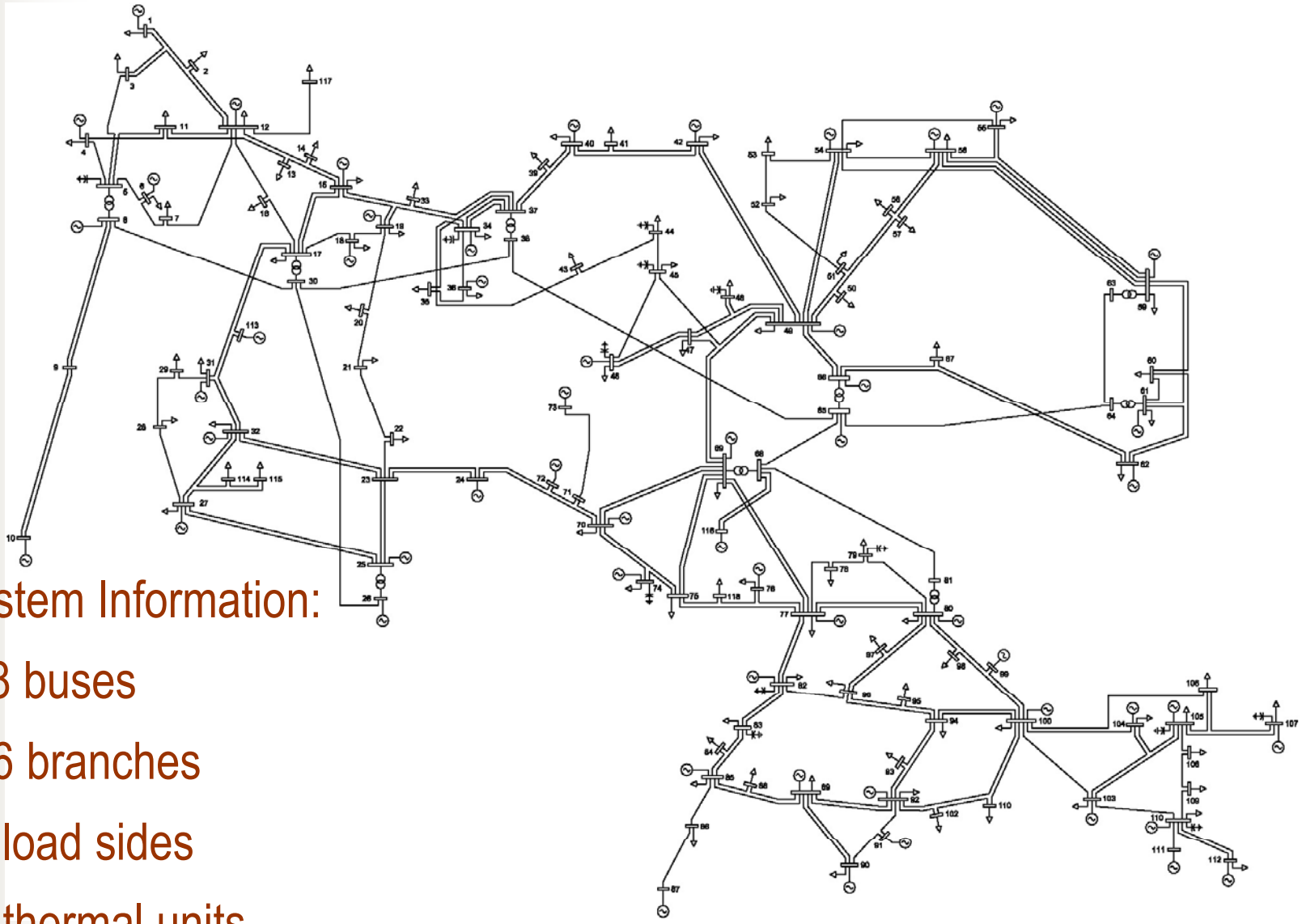
- For a fixed VOLL, we calculate the incremental load shedding cost as $OC_{p1} - OC_{p2} / LS_{p2} - LS_{p1}$, where OC_{p1} and LS_{p1} are operation cost and load shedding at P1. The incremental load shedding cost represents the marginal cost of a small incremental LOLE (i.e., LOLE2-LOLE1)



Case Study

- 118-bus system
  - Variation of operation cost and load shedding as a function of security
  - Impact of load shedding price on optimal point
  - Impact of fuel price on optimal point

One-Line Diagram of IEEE 118-Bus System



System Information:

118 buses

186 branches

91 load sides

54 thermal units

System Data

Long-term Group Fuel Consumption Constraints

Fuel	Take-or-pay Contract (MBtu)	Available Supply (MBtu)
Coal (FGroup 1)	65,000,000	75,000,000
Oil (FGroup 2)	-	7,000,000
Gas (FGroup 3)	9,000,000	Unlimited

Long-term Group Emission Allowance Constraints

Emission	Max allowance (Lbs)
SO_2 (EGroup 1)	8,000,000
SO_2 (EGroup 2)	200,000
SO_2 (EGroup 3)	1,600,000
NO_x (EGroup 1)	3,500,000
NO_x (EGroup 2)	500,000
NO_x (EGroup 3)	700,000

System Data (Cont'd)

Weekly Peak Load As Percentage Of Annual Peak Load

Week	1	2	3	4
Peak Load (%)	86.2	90.0	90.0	88.0
Week	5	6	7	8
Peak Load (%)	88.0	84.1	83.2	80.6

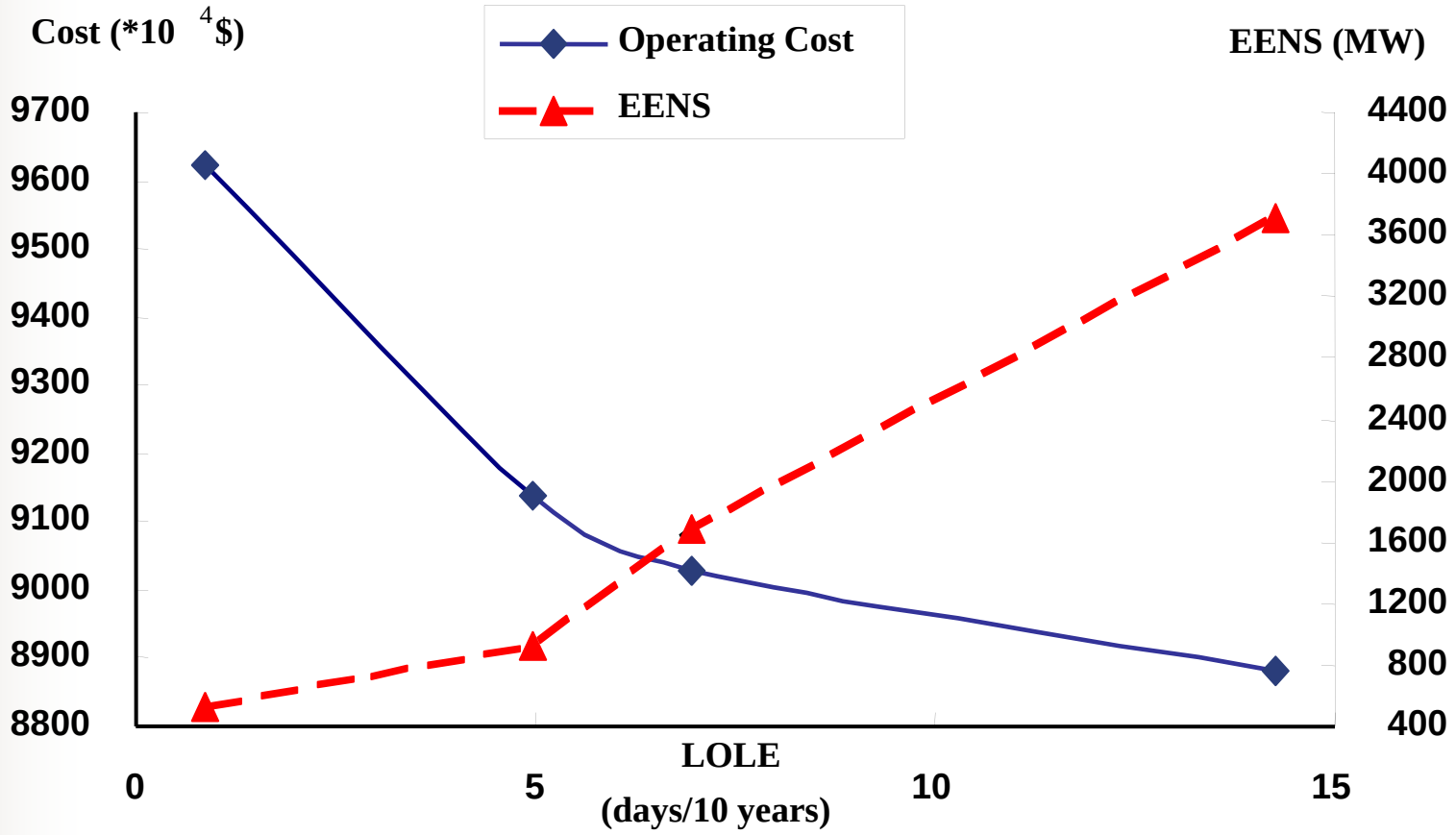
Fuel and emission group

Group	Index of Units
FGroup 1 (Coal)	4 5 7 10 11 14 16 19 20 21 22 23 24 25 26 27 28 29 30 34 35 36 37 39 40 43 44 45 47 48 51 52 53
FGroup 2 (Oil)	31 32 33 38 41 42 46 49 50 54
FGroup 3 (Gas)	1 2 3 6 8 9 12 13 15 17 18
EGroup 1	10 11 16 21 22 23 24 28 29 30 34 35 36
EGroup 2	31 32 33
EGroup 3	8 9 15 17 18

Results for Different LOLE Values

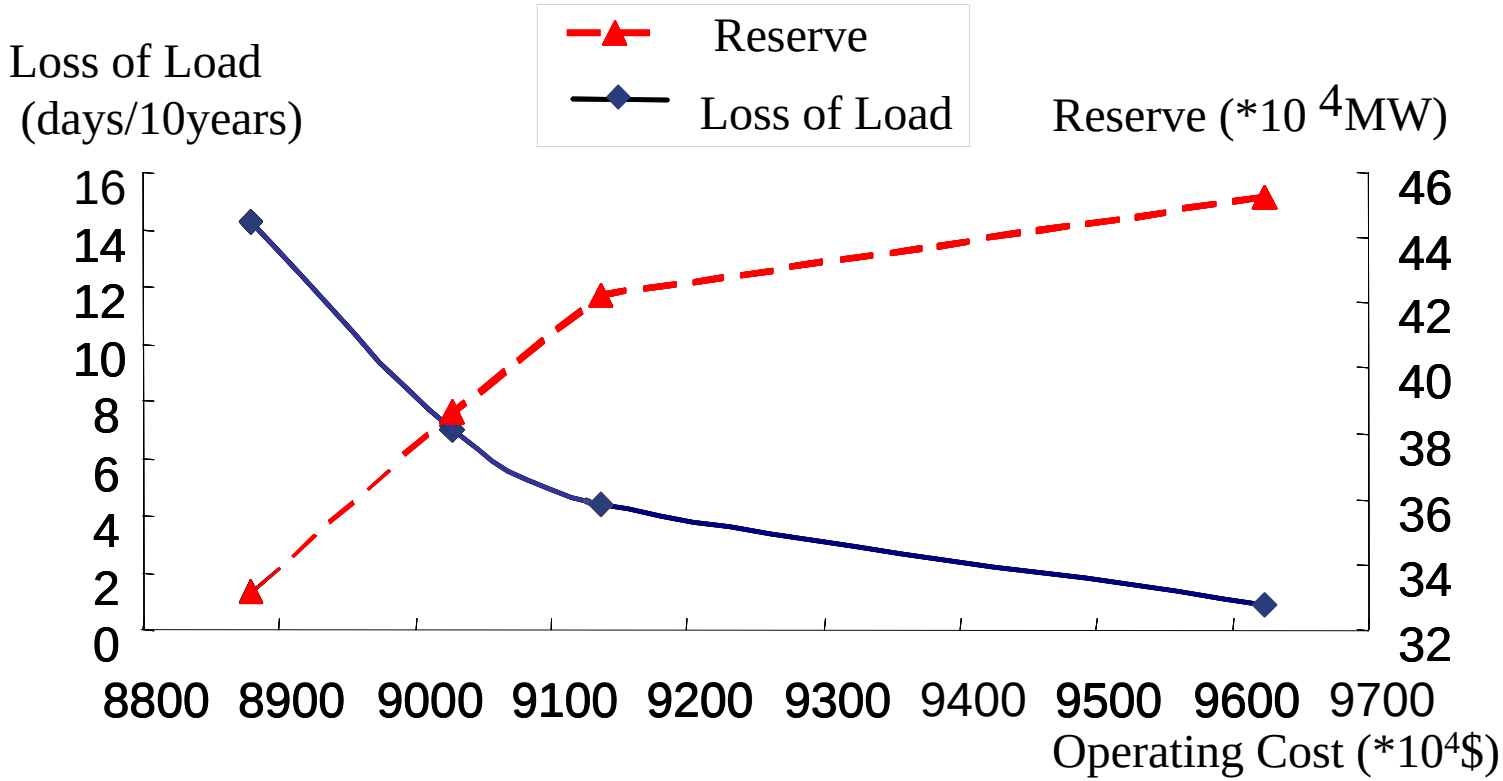
LOLE(in 10 years)		1 day	5 days	10 days	15 days	Deterministic
Operating cost (*$10^4$$)		9623.89	9136.65	9027.18	8880.03	8786.37
EENS (MW)		532.21	920.85	1692.74	3714.02	7040.22
Max LOLE (in 10 years)		0.85 day	4.97 days	6.95 days	14.27 days	31.7 days
Min reserve (MW)		905.33	579.98	471.25	382.28	254.21
Coal (MBtu)		72,443,639	74,059,858	74,112,301	74,279,656	73,987,725
Oil (MBtu)		6,475,901	5,945,081	4,904,175	4,426,361	3,887,508
Gas (MBtu)		12,111,537	9,675,367	9,572,179	9,784,396	11,346, 726
SO_2	EGp_1 (Lbs)	7,545,283	7,574,098	7,617,717	7,619,974	7,962,311
	EGp_2 (Lbs)	194,025	136,119	120,422	118,074	79,479
	EGp_3 (Lbs)	1,534,584	943,378	942,819	948,722	1,427,691
NO_x	EGp_1 (Lbs)	3,029,639	3,018,115	3,046,682	3,047,591	3,184,927
	EGp_2 (Lbs)	93,619	74,441	64,174	47,237	31,791
	EGp_3 (Lbs)	653,839	377,351	353,122	361,495	571,073

Variation of Cost and EENS



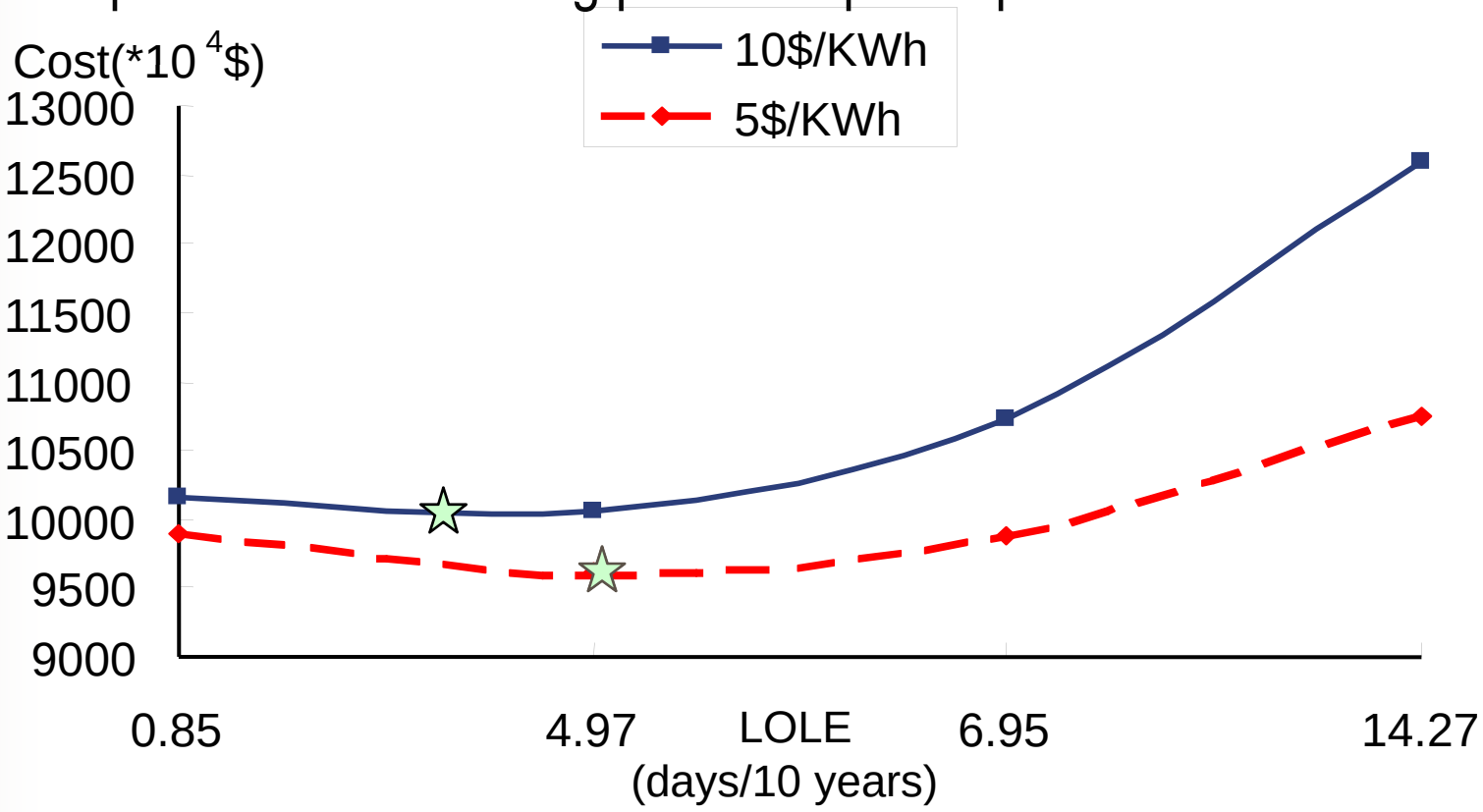
Sensitivity Analysis

- Relationship between Reserve and LOLE



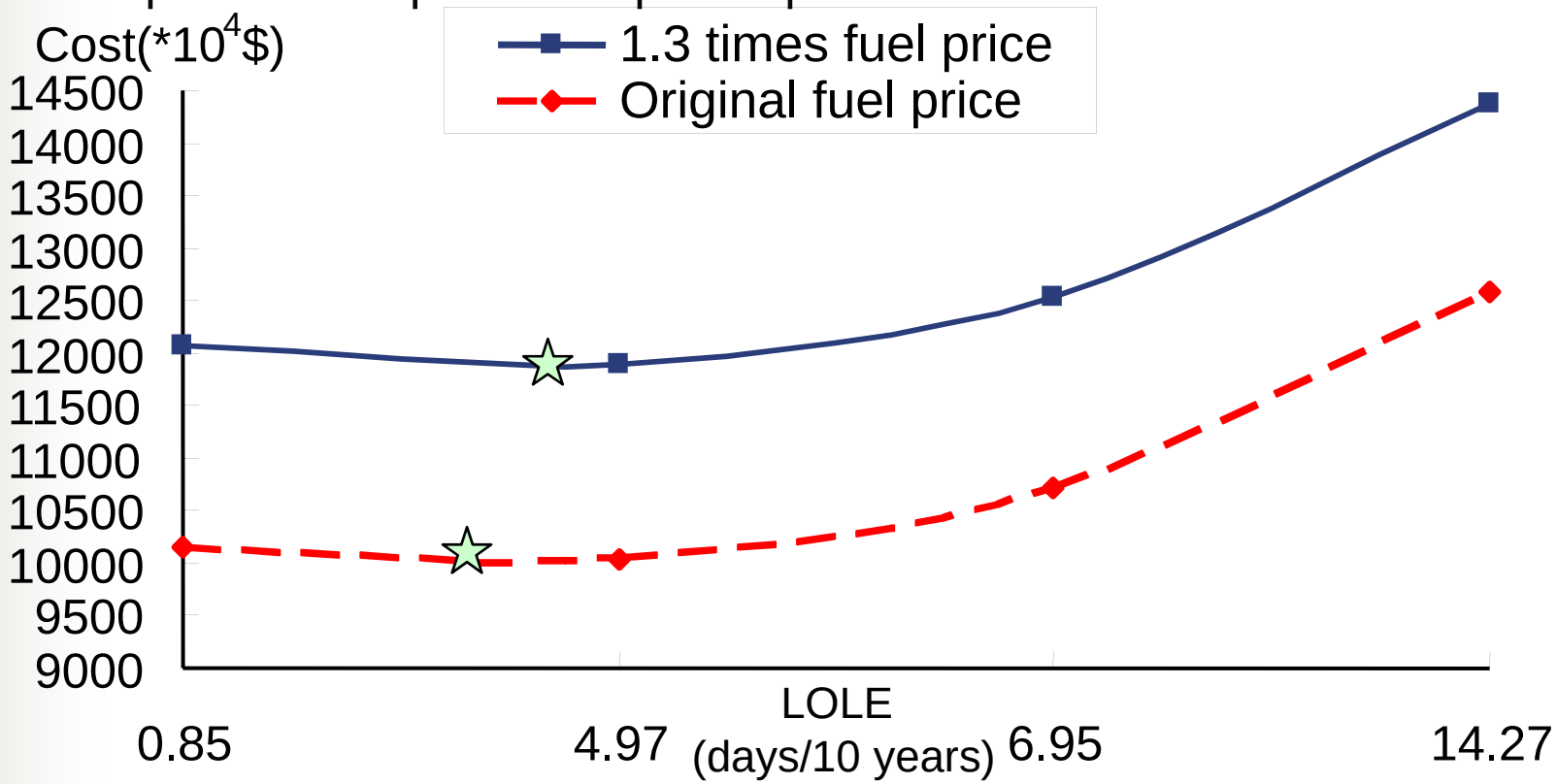
Sensitivity Analysis (Cont'd)

- Impact of load shedding price on optimal point



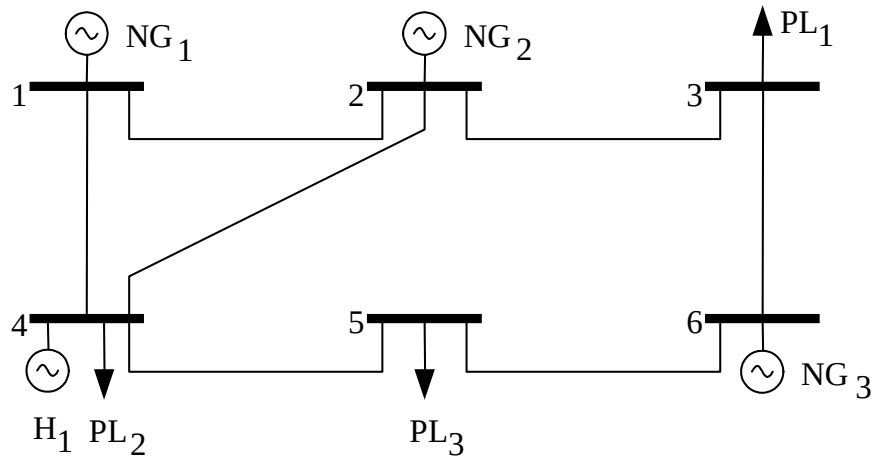
Sensitivity Analysis (Cont'd)

- Impact of fuel price on optimal point



Case Studies for Hydro Constraints

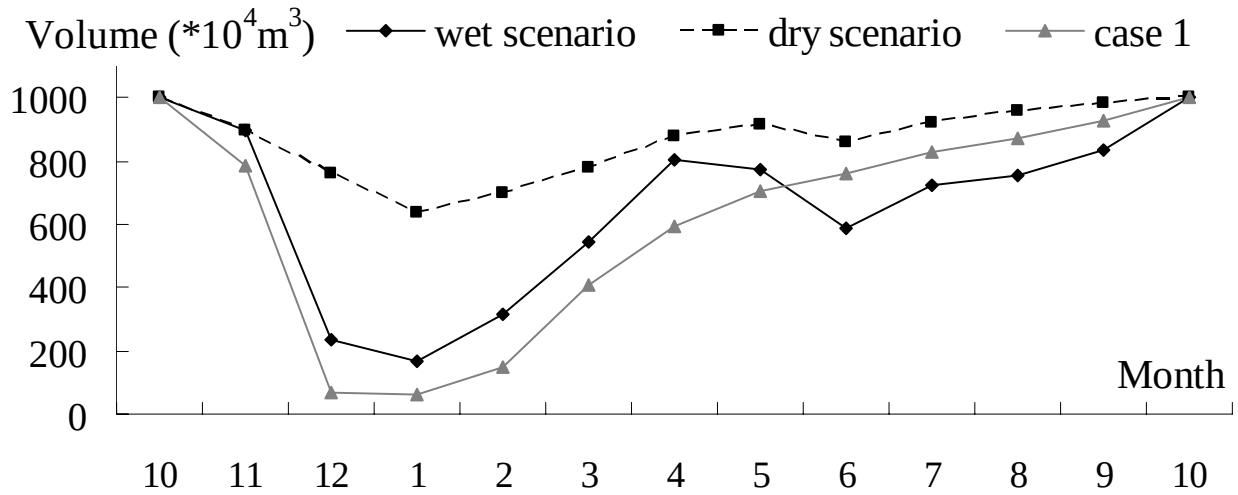
- A 6-bus system
  - 3 gas-fired units, 1 hydro unit and 7 transmission lines
  - The system is tested for a one-year case (from November to the October in the next year) with the annual peak power load of 330MW and annual peak gas load of 6000 kcf .
  - The maximum allowed load shedding for each load bus is set to be the load value at designated bus, with the VOLL of 5000$/MWh for the first 10% of load at designated bus and 2000$/MWh for the remaining.



- Two cases are studied to illustrate the effect of midterm water and gas optimal usage on power systems reliability
  - Case 1: A deterministic solution is presented and its impact on the system reliability is discussed. The optimization of deterministic model utilizes as much water as possible to supplement the natural gas usage in the winter season (November-January with highest gas loads). The impact of the deterministic solution on the system reliability is considered by optimizing a scenario-based stochastic model for the remaining months of February-October by utilizing terminal volumes at the end of January as the initial condition.
  - Case 2: The proposed two-stage stochastic optimization model is discussed. The first-stage covers the first month, and the second-stage includes the rest 11 months via scenarios. System component outages, power and gas load uncertainties, and natural water inflow uncertainties are all taken into consideration.

- Summary
  - The proposed two-stage stochastic optimization is considered for optimizing the midterm water and gas usage with uncertainties.
  - The load shedding is reduced to 440.90 MWh from 460.91MWh, and the total number of load shedding occurrence is reduced to 71.07 hours in one year from 96.465 hours in one year.
  - Water resource stored in the reservoir, previously fully utilized in the winter in case 1, now is partly allocated in the summer for peak-shaving, which reduces the load shedding occurrence in the summer and the social cost is reduced by 5.08% (i.e., 39,585,164.34 – 37,572,145.9 / 39,585,164.34).

- In case 1, the water resource stored in the reservoir is used as much as possible when the future natural water inflow situation is not considered.
- Two scenarios, a dry and a wet year, shows that water used in the winter has to be limited, to ensure enough water for peaking-shaving in case of a dry weather in the future.
- The results reveal the necessity of incorporating the two-stage stochastic optimization model for the midterm water and gas management policies to enhance the systems reliability.



Conclusions

- This presentation proposed a two-stage stochastic programming model for optimizing the midterm water and gas usage with uncertainties.
- The probabilistic reliability criteria are incorporated into the midterm stochastic unit commitment problem, in which both power network and gas network security are checked and uncertain characteristics of power systems, including component outages, power and gas load uncertainties, and natural water inflow are considered.
- Propose Monte Carlo simulation and scenario-based techniques to form a stochastic model for the long-term SCUC solution

Conclusions

- Adopt LOLE and EENS indexes for calculating the cost of power system reliability based on stochastic long-term SCUC problem
- Provide more reliable decisions on energy allocation, fuel consumption, emission allowance, and long-term utilization of generators and transmission capacities.
- Different from previous reliability analysis work, which were based on ED problem, this work provides a global reliability analysis based on stochastic SCUC solution
- The results reveal the effects that water management policies have on the systems reliability. It shows that the proposed two-stage stochastic optimization model improves power system reliability and decreases the social cost by optimally allocating natural water and gas usage in a midterm horizon.