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SUSTAINABLE ENERGY

Prof. Michael W. Golay
Nuclear Engineering Dept.

Energy Supply, Demand, and Storage Planning

The Example of Electricity

PRESENTATION OUTLINE

I. Introduction
II. Demand Variations for Electricity
III. Electricity Supply Availability
IV. Locational-Based Electricity Markets

INTRODUCTION

- Due to Large Fluctuations in Supply and Demand, Energy Systems Must be Able to Respond to Changing Conditions in Order to Meet Consumer Energy Needs Across Time and Space
- Examples
  - Oil products: home heating oil and gasoline
  - Natural gas
- Electricity is the Most Pronounced Example

I. Demand Variations

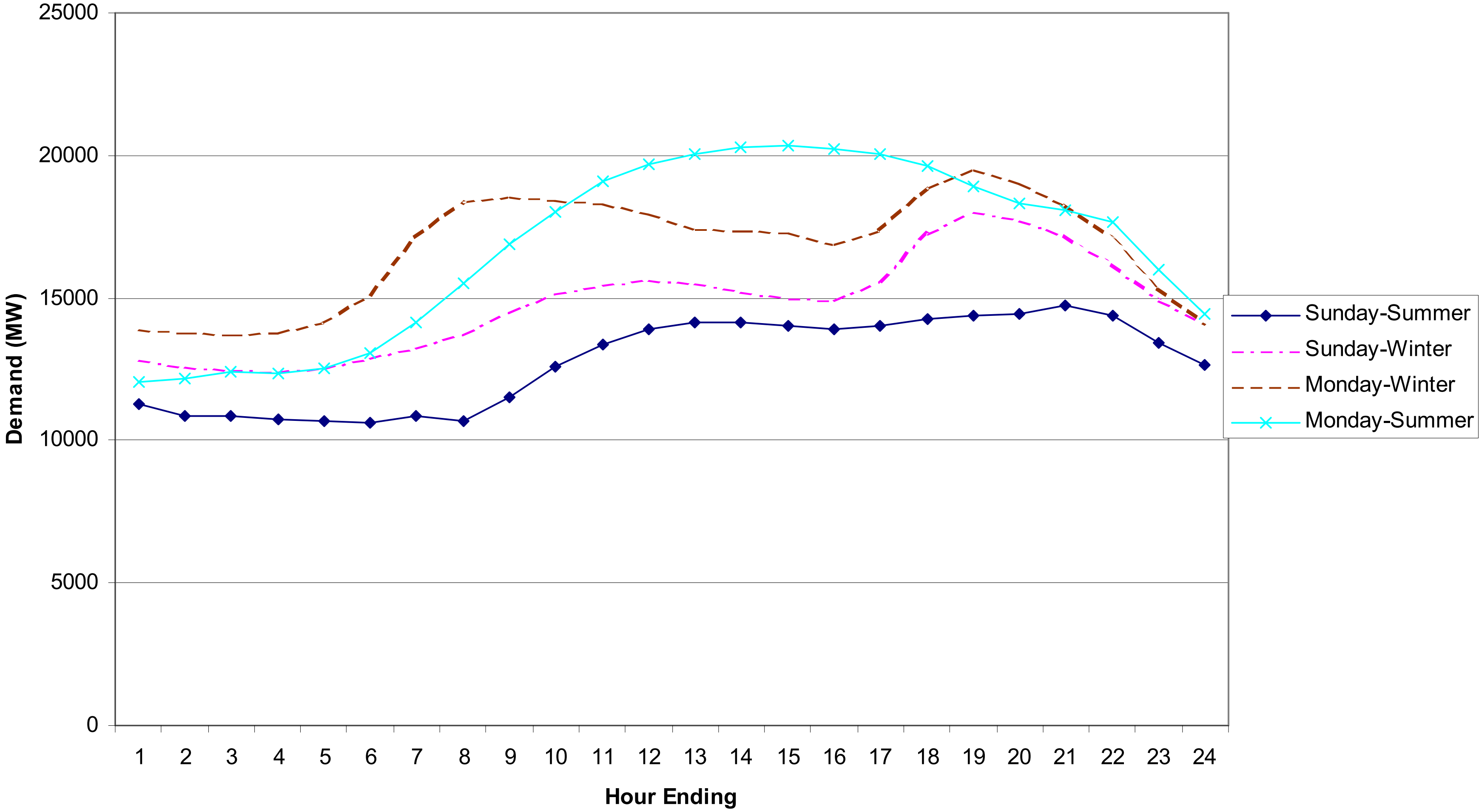
ANNUAL AND SEASONAL DEMAND VARIATIONS

- Annual
  - Driven by economic growth
  - Rough rule of thumb
    - Developed economies: electric growth rates approximately equal to economic growth rates
    - Developing economies: electric growth rates approximately twice that of economic growth rates
- Seasonal Changes Due to
  - Weather
  - Changes in usage (e.g., lighting, air conditioning)

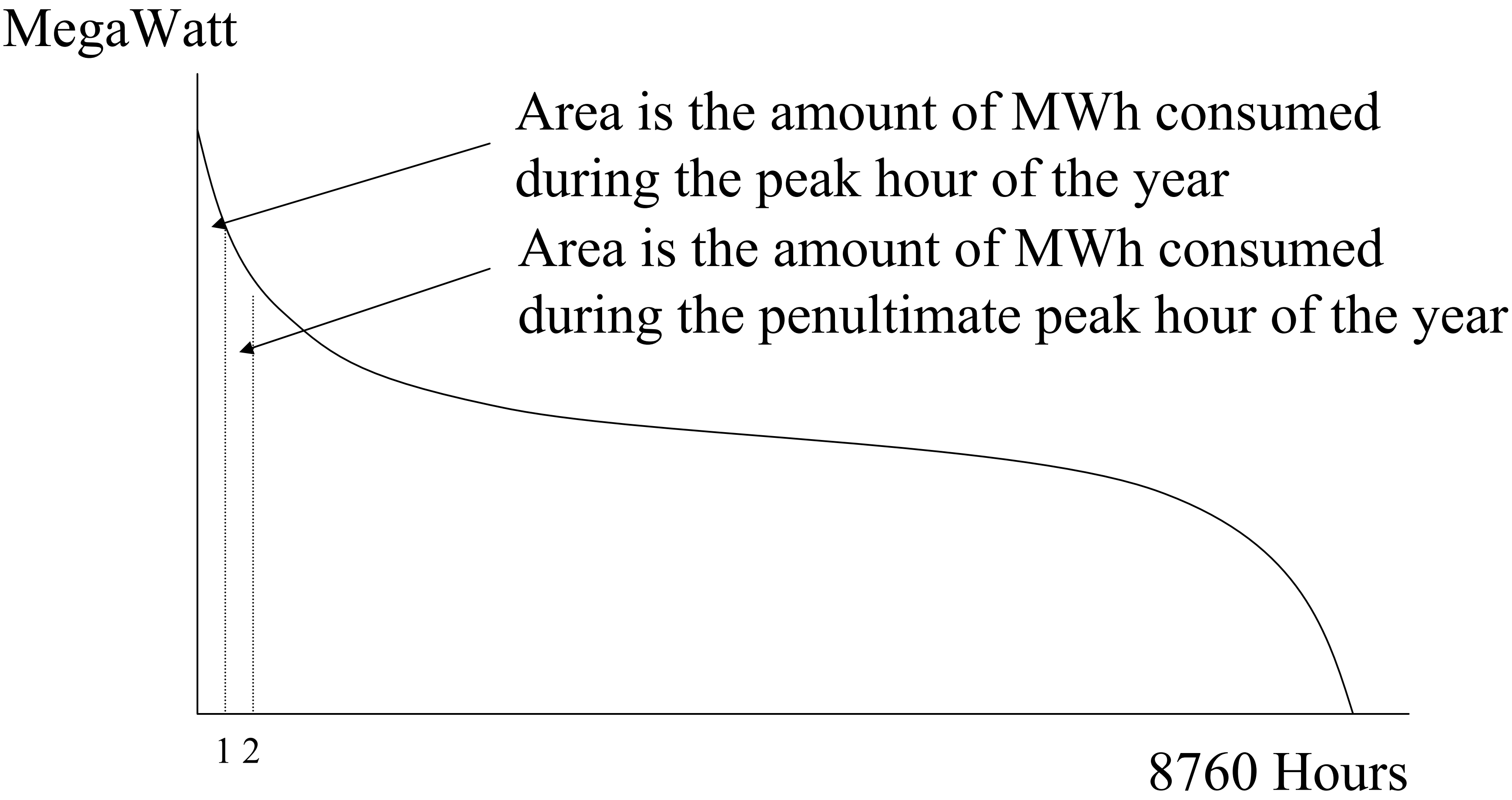
WEEKLY AND DAILY DEMAND VARIATIONS

- Weekly Variations Driven by Business Day vs. Holiday/Weekend
- Daily Variations Driven by Time of Day, Weather, and to a Small Extent Spot Electricity Prices (so far)

HOURLY ELECTRICITY DEMAND IN NEW ENGLAND DURING TYPICAL SUMMER AND WINDER MONDAYS AND SUNDAYS



ANNUAL LOAD DURATION CURVE

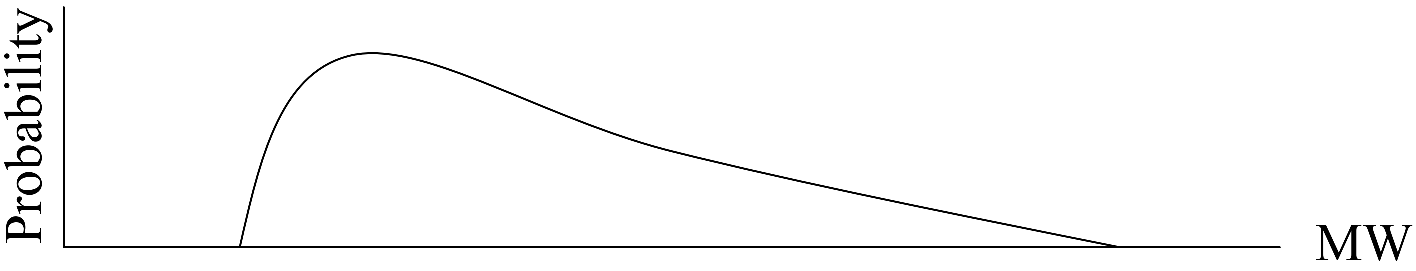


Area is the amount of MWh consumed during the peak hour of the year

Area is the amount of MWh consumed during the penultimate peak hour of the year

USEFUL FACTS REGARDING DEMAND VARIATIONS

- Demand is an Empirically Determined Probability Distribution Usually with a “Long Tail”
  - Lognormal type shape
  - Sometimes modeled as a Gamma Distribution



- Summer Peaks are More Pronounced Than Winter Peaks

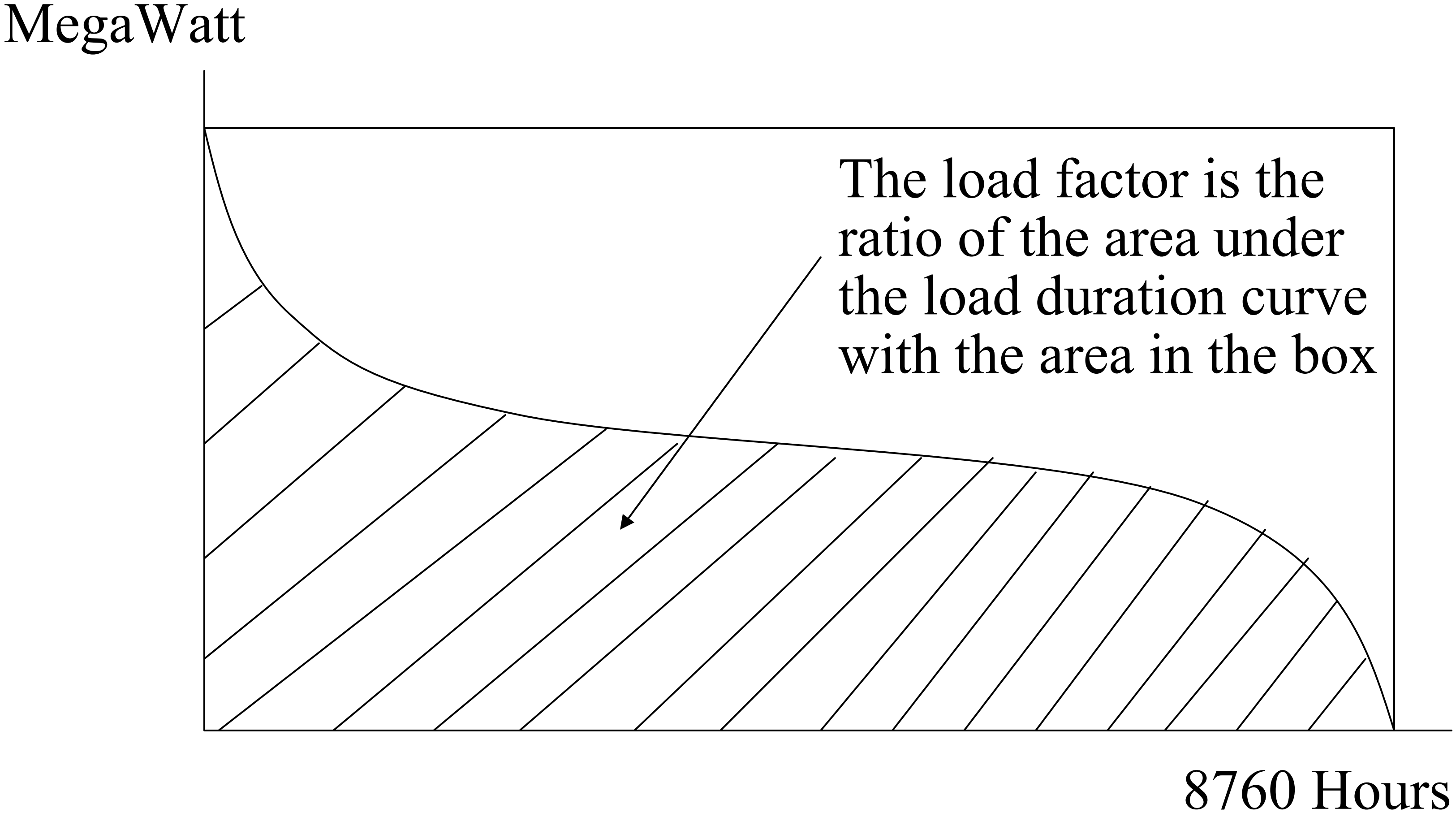
SIMPLE DEMAND CALCULATION

- Problem
  - What is the amount of generation capacity needed to supply 20 GW of peak load?
  - If the system's load factor is .65, what is the average amount of demand?
- Assumptions
  - 3% transmission losses and 6% distribution losses
  - 20% capacity factor (amount of extra capacity needed beyond system peak to account for outages - to be discussed below)

SIMPLE DEMAND CALCULATION (Con’t)

- Solution
  - Generation Capacity = 1.20 *[20 GW + 20 GW* 0.09] = 26.2 GW
  - Load Factor = Average Demand/Peak Demand
  - ┌ Average Demand = 0.65*[20 GWh] = 13.0 GWh

ANNUAL LOAD DURATION CURVE AND LOAD FACTOR



The load factor is the ratio of the area under the load duration curve with the area in the box

II. Supply Variations

SPATIAL DEMAND VARIATIONS

- Size of Typical Electricity Wholesale Markets
  - England and Wales
  - Northeast area of North America
  - Within in these large areas, there are multiple control areas (subregions that dispatch generation units within them) but with wholesale transactions among control areas
    - Control areas
    - Independent system operators (ISOs)
    - Regional transmission organizations (RTOs)
- Spatial Demand Variations Caused by
  - Differences in loads
    - Industrial vs. residential
    - Regional weather patterns
    - Time zones

SUPPLY OPTIONS

- Multiple Types of Generation Units to Address Demand Variations
  - Baseload (run of river hydro, nuclear, coal, natural gas CCGT)
  - Intermediate (oil, natural gas CCGT)
  - Peaking (oil, diesel, natural gas CT, pumped storage)
  - Non- dispatchable (wind, solar, wave)
- Tradeoffs
  - Capital and fixed costs vs. operating costs, which are primarily driven by fuel costs and heat rate
  - Lower operating costs vs. operational flexibility (e.g., start up time, ramp rate)
  - Who bears these costs influences investment decisions
- Storage Options are Expensive (e.g., pumped storage, hydro reservoirs)

TRANSMISSION INFRASTRUCTURE

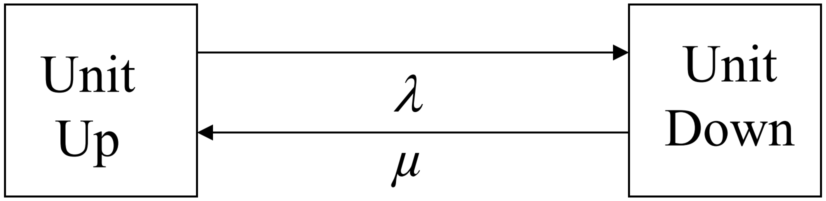
- AC Transmission Lines ($V \geq 115$ kV > 10,000 km)
- DC Transmission Lines
- Switch Gear, Transformers and Capacitor Banks
- Distribution Lines and Support Hardware

ECONOMIES OF SCALE VS. DEMAND UNCERTAINTY

- Average Costs per MWh Decrease with the Capacity of a Generation Unit (Economies of Scale)
- ┌ It is Less Expensive to “Overbuild” a System and Let Demand “Catch Up”
- But, Due to Uncertainty in Demand (Which is Influenced by Price Feedbacks), Future Demand May Not Materialize Quickly Enough to Justify the Additional up Front Capital Costs (Option Value)
- These Concepts Will be Discussed Later in the Course

GENERATION AVAILABILITY

- Availability - The Probability That a Generation Unit Is Not on Forced Outage at Some Future Time (not the conventional definition of availability because it excludes planned maintenance)
  - Availability = MTTF/(MTTF + MTTR)
  - MTTF is the mean time to failure
  - MTTR is the mean time to repair
  - Expected failure rate = 1/MTTF = λ
  - Expected repair rate = 1/MTTR = μ



Unit Up

λ

μ

Unit Down

- Generation Availabilities Range from 0.75 to 0.95

AVAILABILITY

Conventional Definition:

The probability that a generation unit will be able to function as required at time, t, in the future.

CATEGORIES OF FAILURES

- Independent Failures - The State of a Generator or Component Does Not Depend on the States of Other Generators or Components
- Dependent Failures
  - Component state-dependent
  - Common-cause failures - the cause of one generator to fail also causes another unit to fail
    - extreme cold weather freezes coal piles
    - earthquakes trip multiple generation units
    - maintenance error results in multiple generation units tripping
  - Safety policies - poor safety performance of one nuclear power unit leads to shutting down other nuclear units
  - Environmental policies

GENERATION UNIT AVAILABILITY DATA (1994-1998)

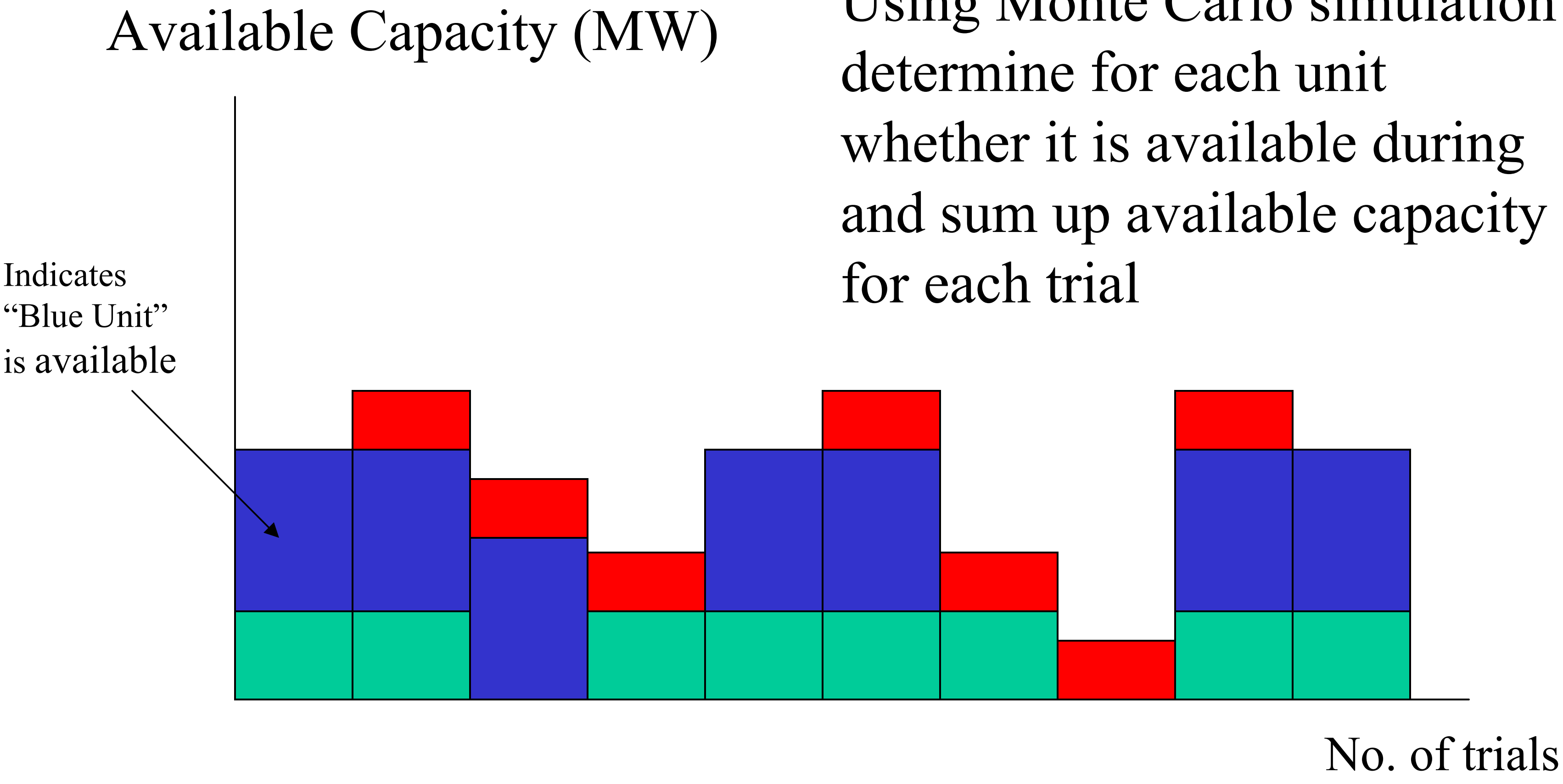
Unit Type	MW Trb/Gen Nameplate	# of Units	Unit-Years	Availability
FOSSIL	All Sizes	1,532	7,126	86.28
Coal	All Sizes	929	4,319	86.37
Primary	1-99	165	707	87.59
	100-199	258	1,203	87.77
	200-299	114	560	86.26
	300-399	88	433	83.93
	400-599	171	799	84.32
	600-799	95	433	87.06
	800-999	25	124	87.07
	1000 Plus	13	60	83.25
Oil	*All Sizes	200	685	85.84
Primary	1-99	64	205	89.65
	100-199	50	174	86.01
	200-299	12	36	84.14
	300-399	21	96	80.53
	400-599	30	91	84.34
	600-799	13	48	85.13
	800-999	9	30	87.89
Gas	All Sizes	466	1,965	86.08
Primary	1-99	145	554	89.43
	100-199	147	624	86.30
	200-299	47	211	85.33
	300-399	41	188	81.60
	400-599	63	296	84.10
	600-799	20	81	80.46
	800-999	3	11	88.29

Unit Type	MW Trb/Gen Nameplate	# of Units	Unit-Years	Availability
NUCLEAR	*All Sizes	125	598	78.00
PWR	All Sizes	71	342	80.62
	400-799	11	52	82.90
	800-999	24	118	82.14
	1000 Plus	36	172	78.90
BWR	*All Sizes	33	159	74.03
	400-799	4	18	80.31
	800-999	13	63	71.80
	1000 Plus	15	75	74.28
CANDU	All Sizes	21	97	75.16
JET	All Sizes	310	1,505	91.40
ENGINE**	1-19	59	294	92.00
	20 Plus	251	1,211	91.26
GAS	All Sizes	768	3,475	90.21
TURBINE**	1-19	199	928	91.81
	20-49	251	1,161	88.70
	50 Plus	318	1,386	90.40
COMB. CYCLE	All Sizes	58	242	91.49
HYDRO	All Sizes	829	3,855	90.30
	1-29	314	1,429	90.88
	30 Plus	515	2,426	89.96
PUMPED				
STORAGE	All Sizes	69	299	85.52
MULTI-BOILER/				
MULTI-TURBINE	All Sizes	75	268	88.92
GEOTHERMAL	All Sizes	18	86	89.67
DIESEL**	All Sizes	161	666	95.34

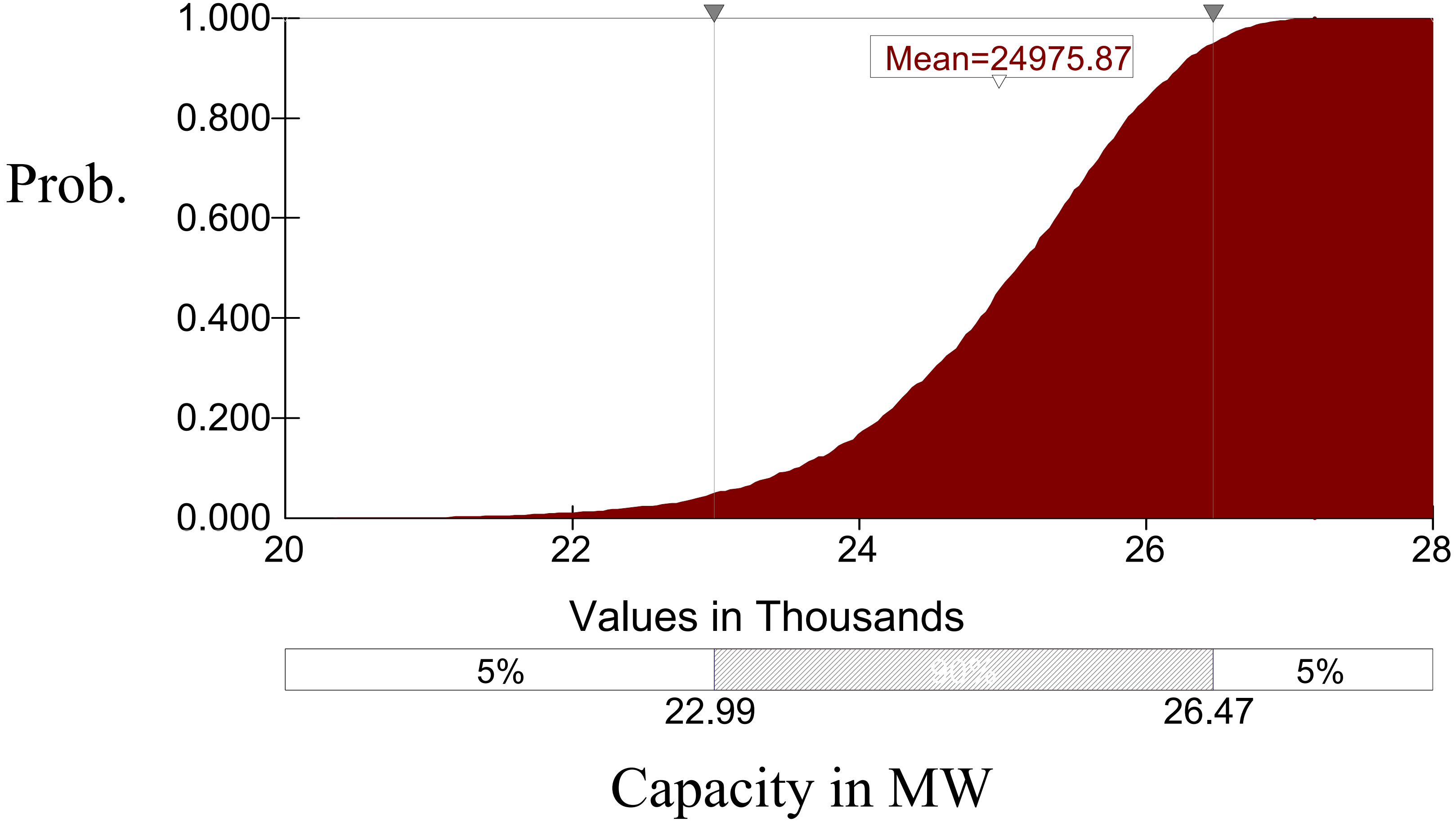
North American Reliability Council, Generation Availability Data Service

MODELING AVAILABLE GENERATION

Using Monte Carlo simulation determine for each unit whether it is available during and sum up available capacity for each trial



CUMULATIVE PROBABILITY DISTRIBUTION OF AVAILABLE GENERATION AND IMPORT CAPACITY IN NEW ENGLAND



SPATIAL ISSUES

- Tradeoff Between the Relative Cost of Transporting Fuel or Electricity
  - Mine mouth coal plants (cheaper to transport electricity)
  - Gas-fired unit in Boston (cheaper to transport nat. gas)
  - Relative cost of land
  - Opportunistic siting (as with IPPs)
- Safety and Emissions
  - Nuclear power plants are usually not located near large population centers
  - Urban areas may have stricter emission restrictions than remote areas
- Distributed Generation (cogen, fuel cells, diesels)

III. Matching Supply and Demand

RELIABILITY AND MATCHING SUPPLY AND DEMAND

- Reliability - The Ability of an Electric Power System That Results in Electricity Being Delivered to Customers Within Accepted Standards and in the Amount Desired.
- The Reliability of the Electric Power System Requires Almost Instantaneous Matching of Supply and Demand
- If a Mismatch Occurs That Results in a Reliability Problem, a Large Number of Electric Customers, Not Just the Ones That Caused the Mismatch, Have Their Service Interrupted
  - e.g., Western U.S. Summer of 1996
- This Type of Economic Externality Does Not Exist in Other Markets (e.g., store running out of newspapers)

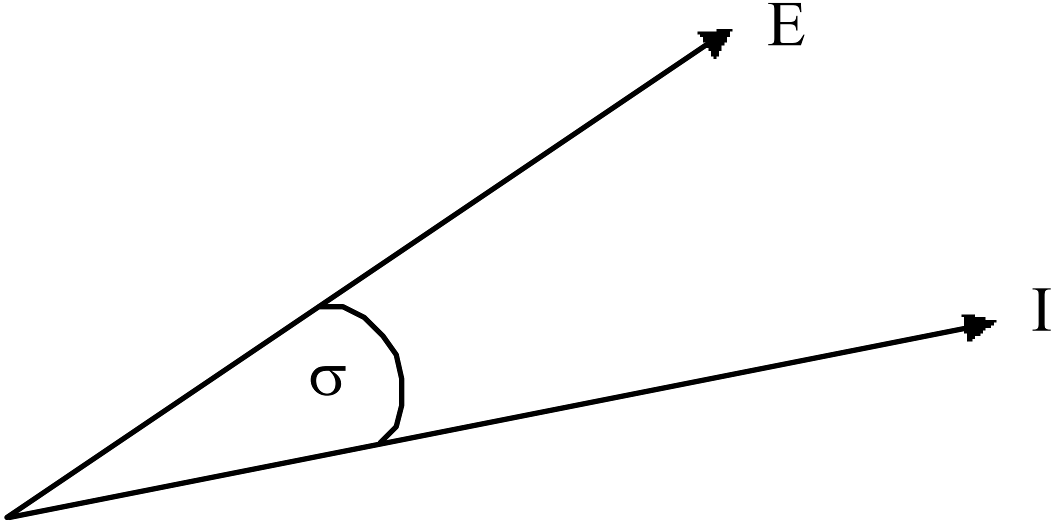
RELIABILITY AND AVAILABILITY TRENDS

- Reliability*: The Probability of Successful Mission Completion.
- Regional Scale Grid System Collapses are Becoming More Frequent (e.g., August 14, 2003, northeast U.S and lower Canada; midwest, 1998; west, 1996; Italy, 2003; London, 2003)
- Deregulation is Resulting in Much Larger Flow of Power Over Long Distances, as “Merchant” Power Plants Contract to Serve Distance (usually industrial loads)
- Grid Components and States are Operating Over Much Broader Ranges and for Longer Times Than Designed For
- Other Power Delivery Aspects (e.g., reactive power) are Excluded From Markets, and are Provided More Poorly

* Conventional definition

III. Locational-Based Electricity Markets

REAL AND REACTIVE POWER



$$\text{Real Power} = |E| \cdot |I| \underbrace{\cos\sigma}_{\text{power factor}}$$

$$\text{Reactive Power} = |E| \cdot |I| \sin\sigma$$

- Grid Stability Requires Spatially Uniform E
- Change σ Permits E to Stay Constant While Changing I

ELECTRIC SYSTEM TIMELINE

Transmission Construction:
3-10 years

Generation Construction:
2-10 years

Planned Generation and
Transmission Maintenance:
1-3 years

Unit commitment:
12 hours ahead for the next 24 hour day

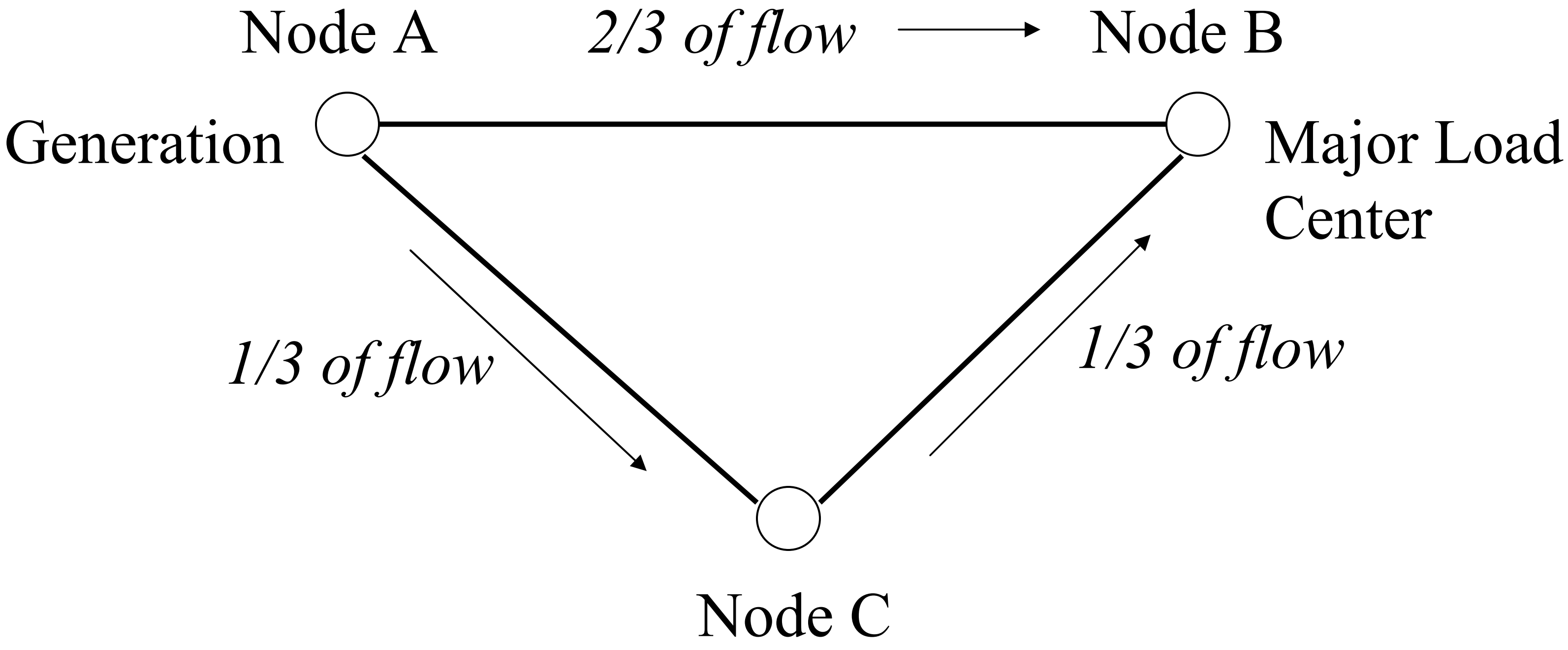
Economic Dispatch:
Every 5 minutes but planned for 6 hours ahead

Time

Build Maintain Schedule Operate Real Time

Note: diagram not drawn to scale

LOOP FLOWS



Assume each transmission line has the same impedance

Flows on each transmission line are be limited for a variety of reasons (see next slide)

LOCATIONAL ELECTRICITY PRICING

- Dispatch Problem Formulation (constrained optimization):
  - Minimize cost of serving electric energy demand
  - Subject to
    - Demand = Supply
    - Transmission constraints
      - thermal limits: prevent damage to transmission components
      - stability: keeping generation units in synchronism
      - voltage: maintain voltage within acceptable limits
      - frequency: maintain frequency within acceptable limits
      - contingency: ability to withstand the failure of components

LOCATIONAL ELECTRICITY PRICING (Con’t)

- Dispatch Problem Solution:
  - Solution method is usually a linear program
  - For each time period (e.g., five minutes), a vector of generation output for each generator
  - For each time period, a vector of prices at each node that reflects the marginal cost of serving one more MWh at that node for that time period
- Nodal Price (t) = Marginal Fuel Cost

  \+ Variable Maintenance Cost

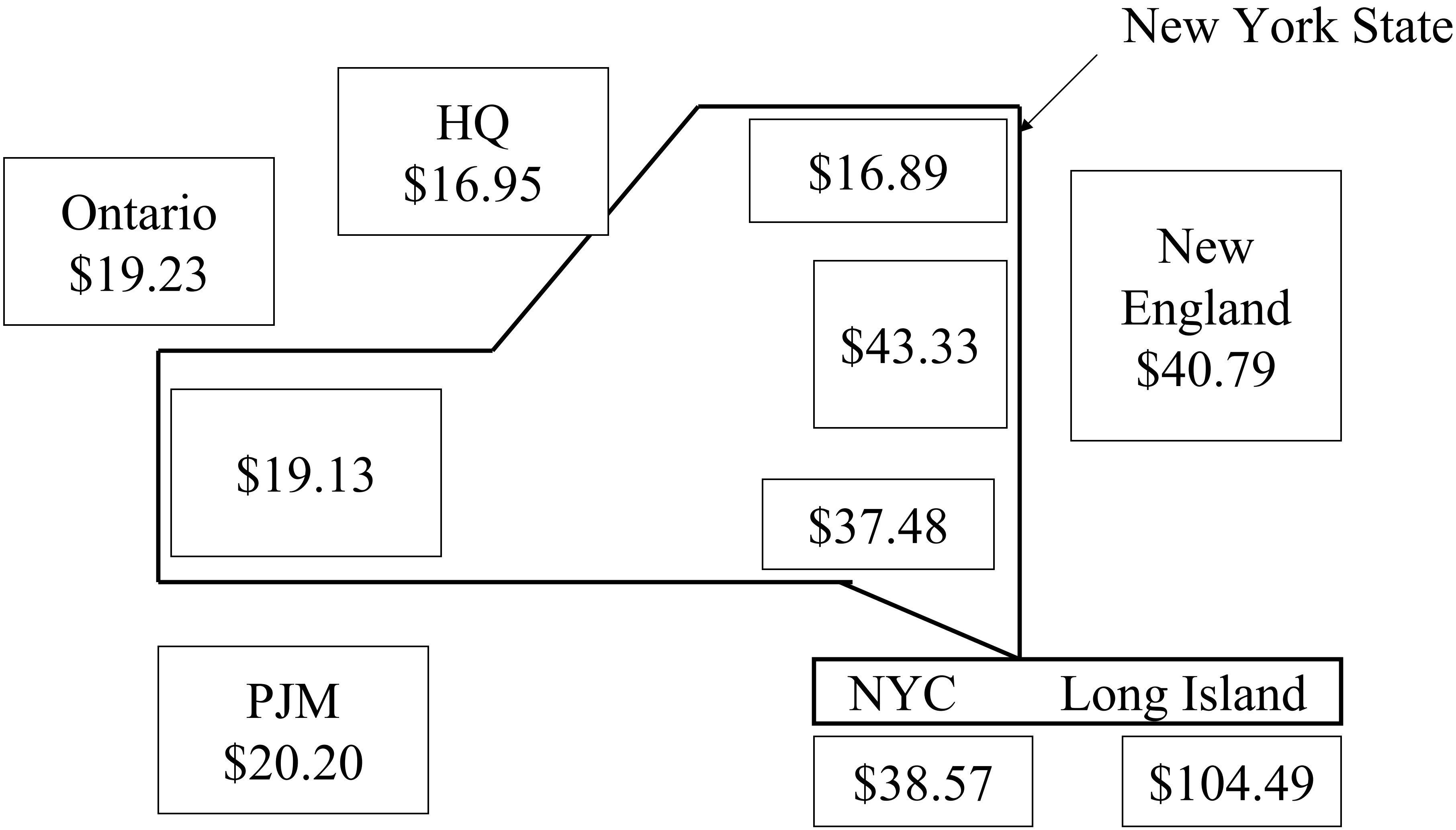
  \+ Transmission Constraints

  \+ Transmission Losses

IMPLICATIONS OF NODAL PRICING

- Prices Could be Negative
  - e.g., a nuclear unit that does not want to turn off during light load conditions because it would not be able to come back on line during higher load periods
- Prices May Increase Dramatically if a Constraint is Binding
  - Cheap generation in the unconstrained area must be back down and replaced with higher cost generation
- Extremely Volatile Prices Across Space and Time

REAL TIME LOCATIONAL PRICES IN THE NORTHEAST ($/MWH)



New York State

HQ
$16.95

Ontario
$19.23

$16.89

$43.33

New England
$40.79

$19.13

$37.48

PJM
$20.20

NYC
$38.57

Long Island
$104.49

DISCUSSION OF CALIFORNIA

- Electricity Restructuring Was Initiated at a Time of Excess Generation Capacity and Motivated to Lower Rates for Retail Customers and Encouraged by British Deregulatory Success
  - Need date for new generation capacity was believed to be distant and beyond the time needed to site and build new generation units
  - Market forces were assumed to be able to address supply/demand mismatches in the interim
  - Desire to complete the bargain between utilities to recover costs of past investments and politicians to lower electricity prices reinforced the above beliefs
- Dramatic Load Growth, Attenuated Market Signals Due to Political Choices, and Time Lags in Siting In-State Generation Has Lead to Supply Shortages