INTEGRATION OF STORAGE INTO POWER SYSTEMS WITH RENEWABLE ENERGY SOURCES: CONSTRUCTION OF A STOCHASTIC SIMULATION APPROACH

presentation by
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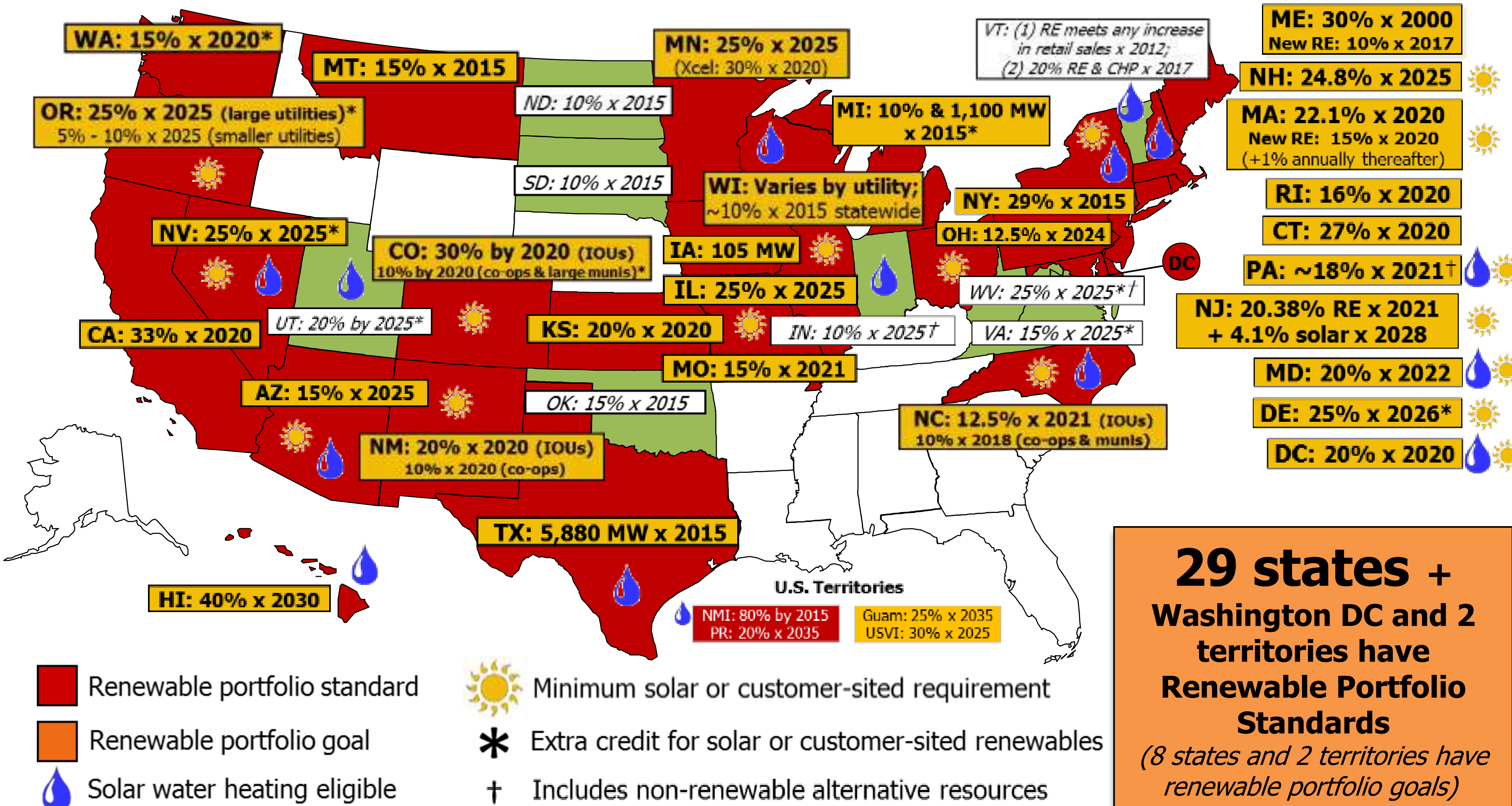
RESEARCH OBJECTIVES

- Construct a comprehensive simulation approach to emulate the behavior of power systems with integrated storage and renewable energy resources in a competitive environment
- Incorporate models for the resources and the loads that capture their salient characteristics – variability and uncertainty, with spatial and temporal dependencies – as well as their interactions over the grid and in the markets
- Demonstrate the simulation approach capabilities with a number of case studies that assess the impacts of storage and renewable resource integration on the power system variable effects

US RENEWABLE PORTFOLIO STANDARDS



29 states +
Washington DC and 2 territories have Renewable Portfolio Standards
(8 states and 2 territories have renewable portfolio goals)

Source: www.dsireusa.org, September 2012

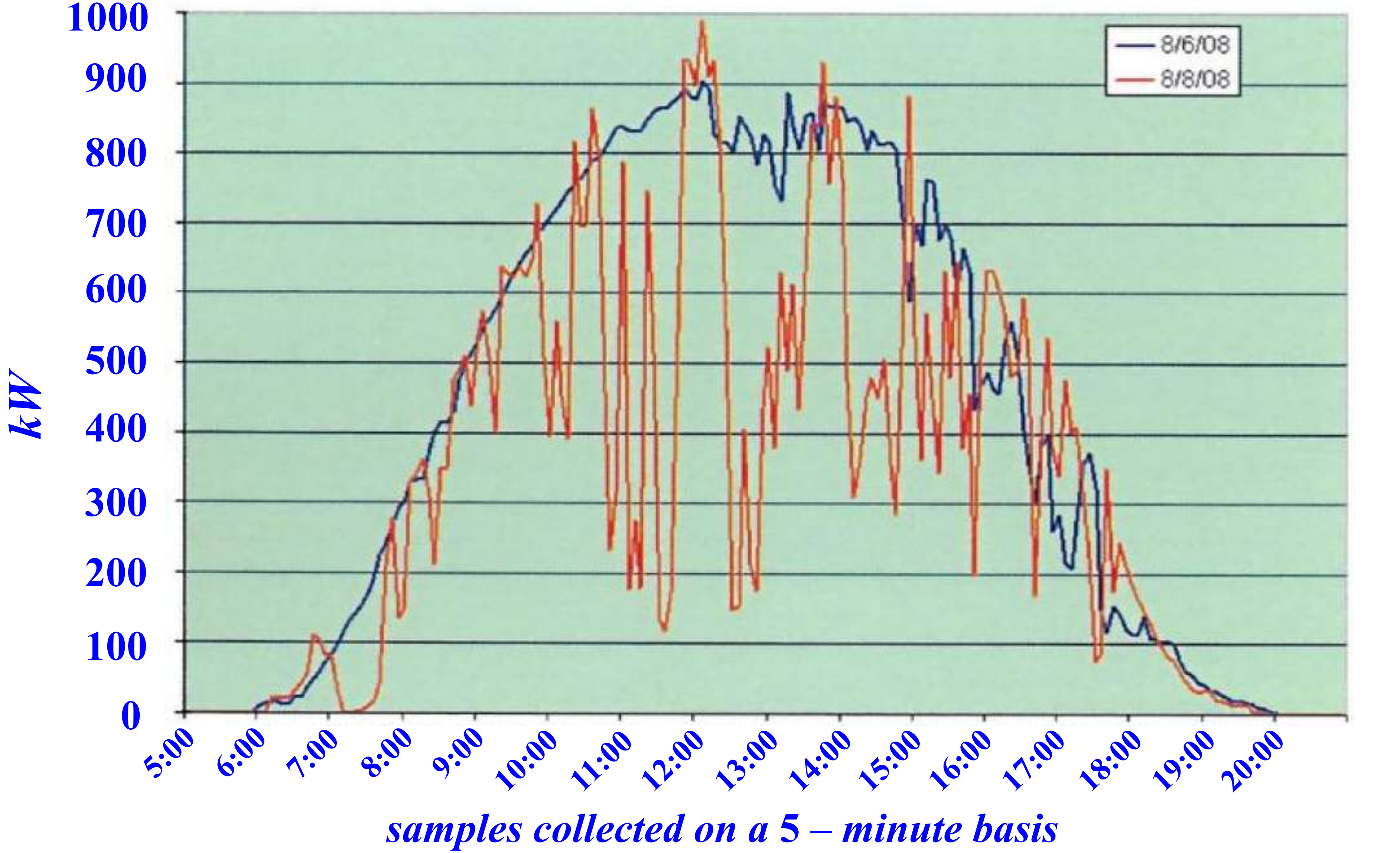
THE CHANGING ENVIRONMENT

- There is a growing worldwide interest in integrating renewable resources, as well as storage resources, into the grid to displace costly and polluting fossil-fuel-fired generation
- The objective of such integration is to push the creation of sustainable paths to meet the nation's energy needs and to veer it towards energy independence
- The context within which this progress unrolls is in the restructured, competitive electricity industry and the advances in the implementation of the Smart Grid

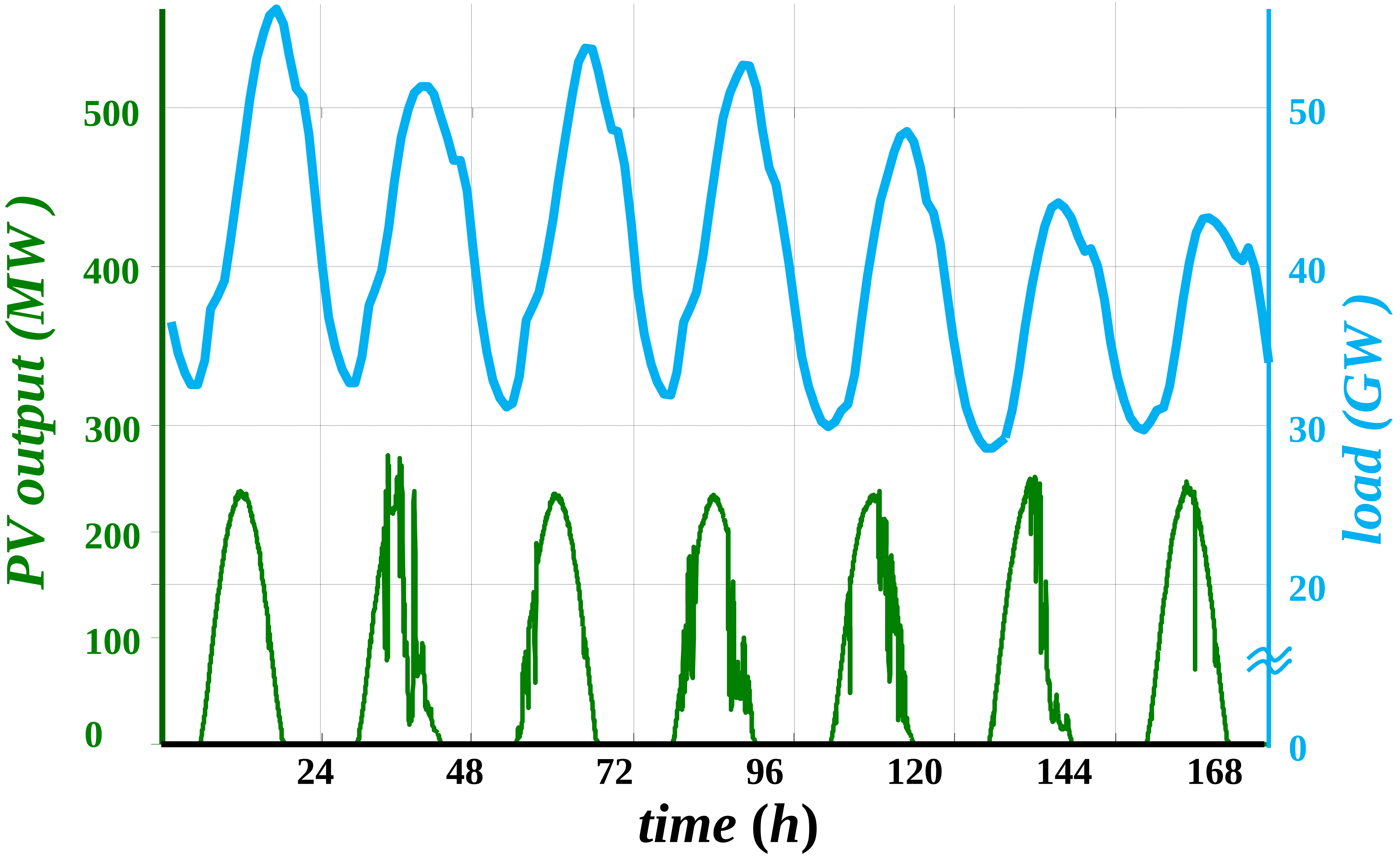
SALIENT CHARACTERISTICS OF SOLAR AND WIND POWER OUTPUTS

- Highly time-dependent nature:
  - variability characteristics
  - intermittency effects
  - seasonal dependence
- Spatially correlated
- Inherently uncertain and difficult to characterize analytically
- Limited accuracy
- Limited controllability / dispatchability

PV POWER OUTPUT OF 1 - *MW* *CdTe* ARRAY IN GERMANY



PV OUTPUT AND LOAD

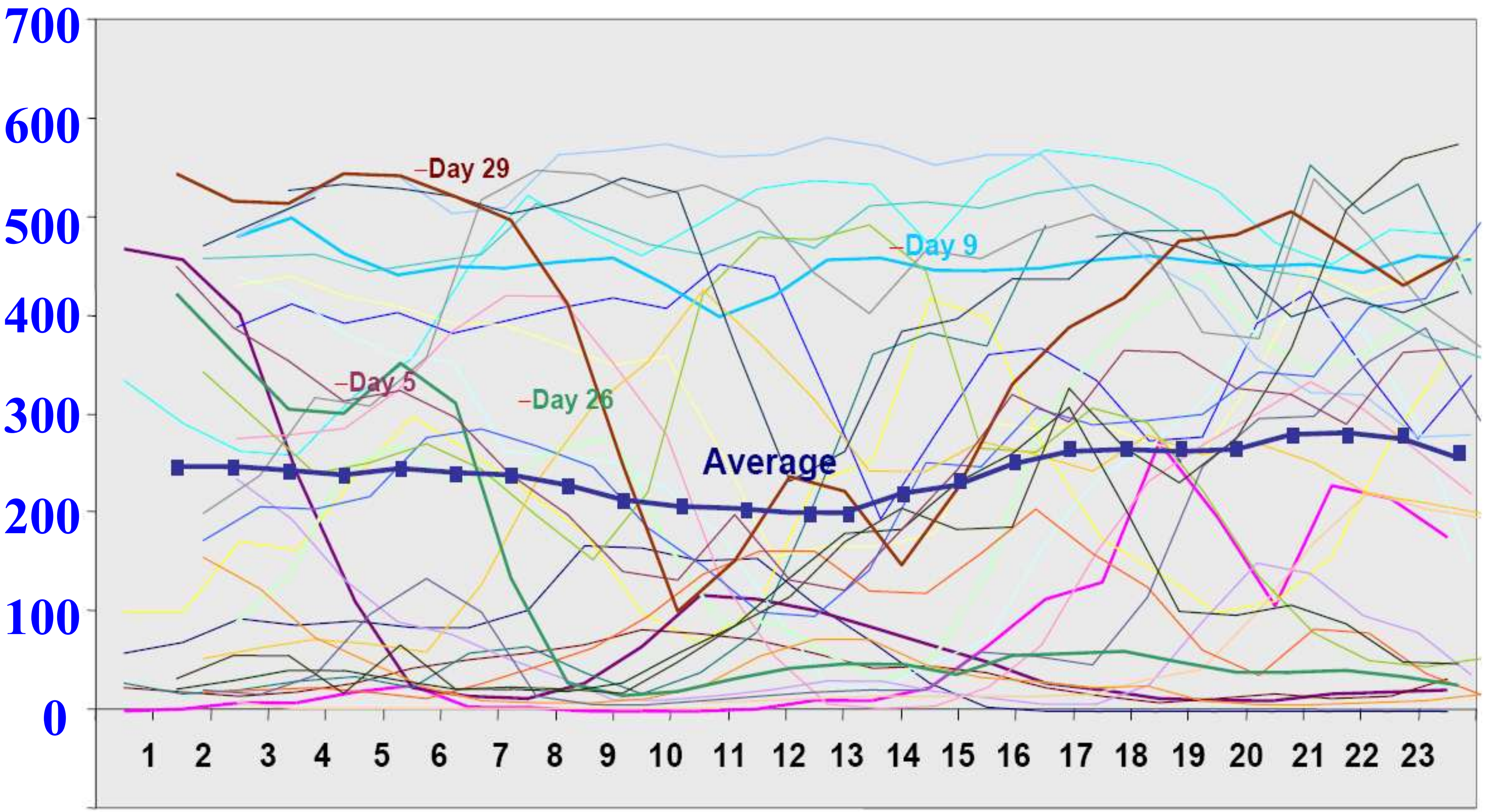


Sources: ERCOT and NREL

CAISO DAILY WIND POWER PATTERNS IN MARCH 2005

MW

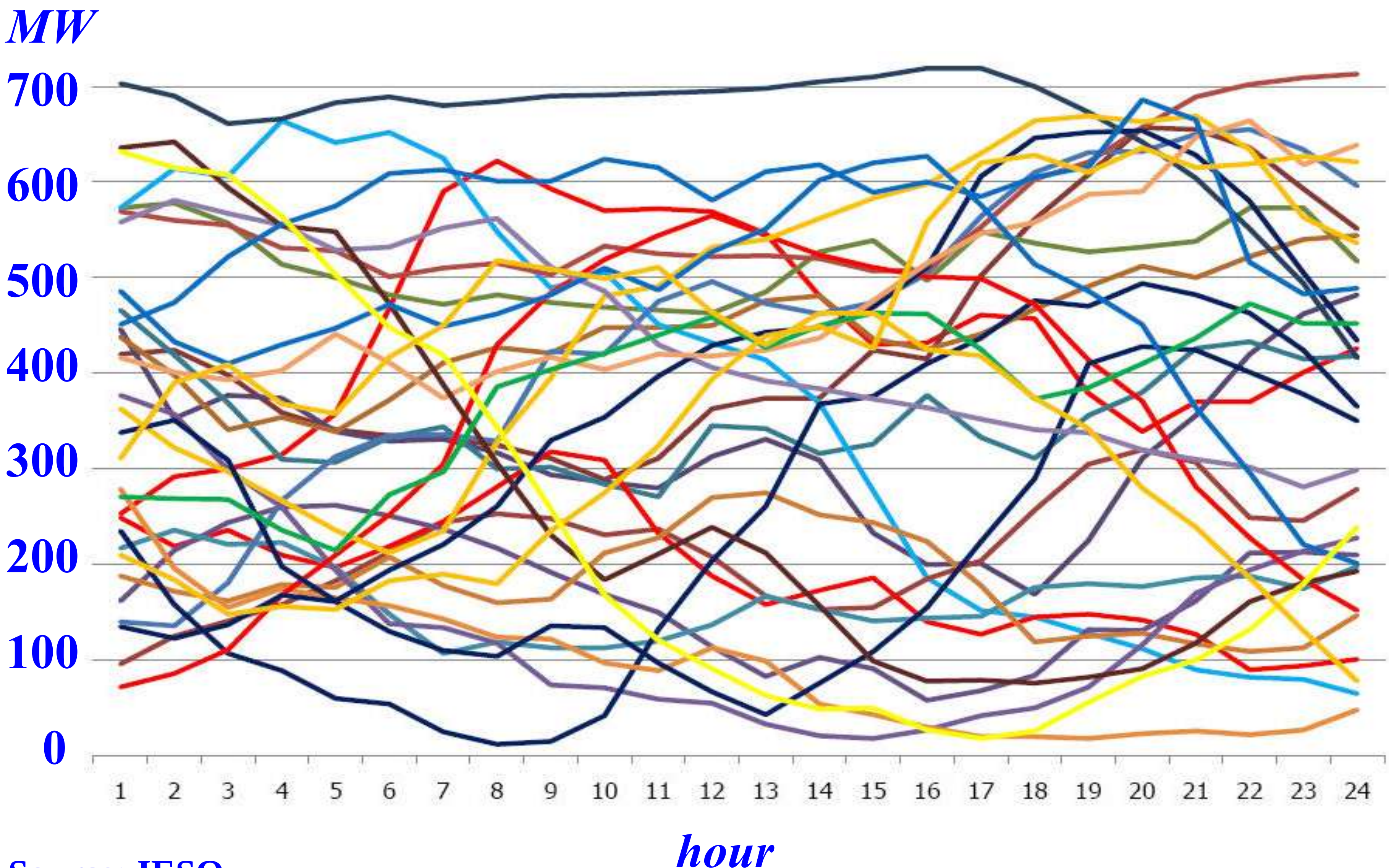
Source: CAISO



hour

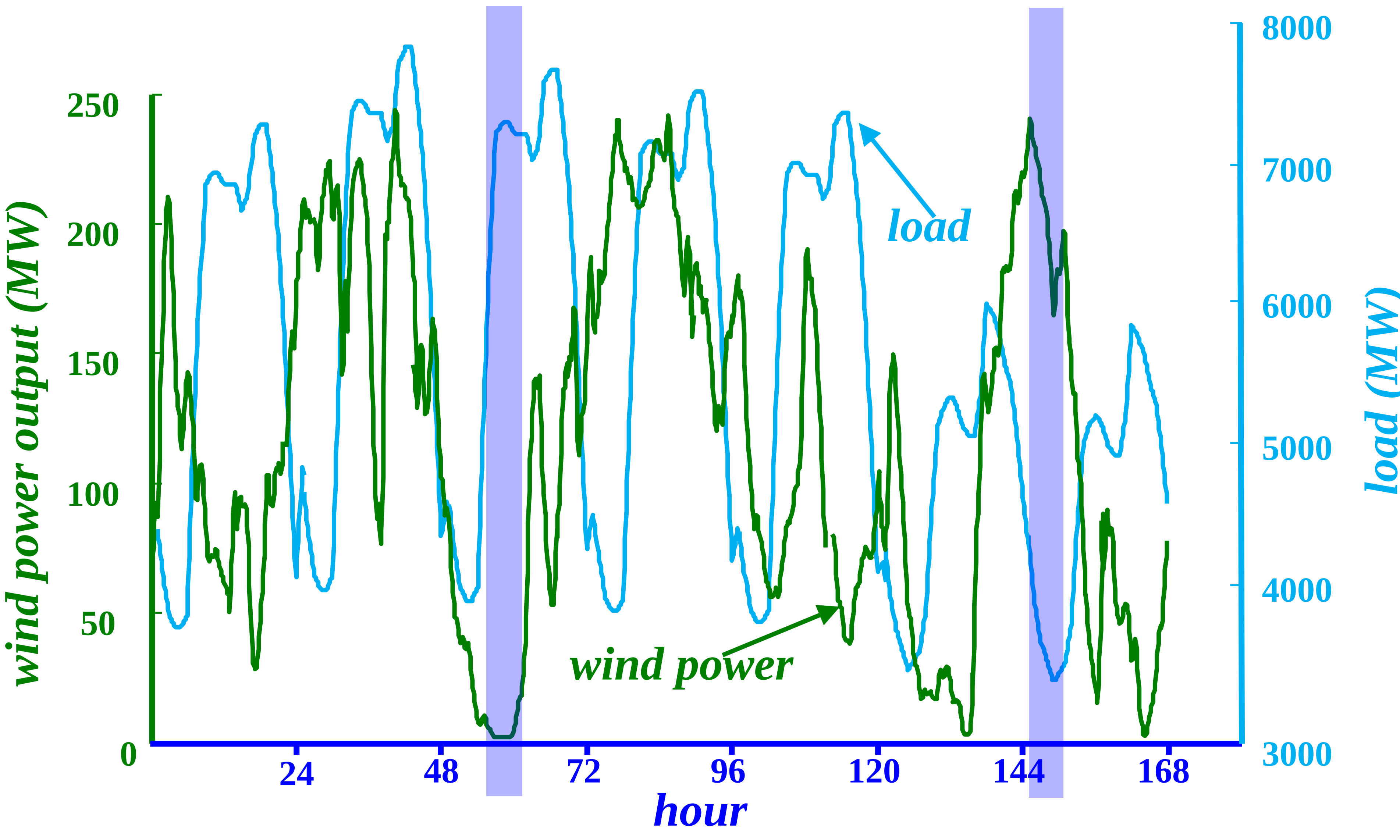
Source: CAISO

ONTARIO DAILY WIND POWER OUTPUT



Source: IESO

MISALIGNMENT OF WIND POWER OUTPUT AND LOAD



ISSUES IN INTEGRATING WIND AND SOLAR RESOURCES

- **Misalignment of the wind power outputs with the load implies that the wind speeds are rarely adequate at times when needed to supply the loads**
- **While morning and mid-day solar power outputs are aligned with the loads, their quick decline after sunset occurs when the loads are still high**
- **The risk of spilling wind due to inadequate loads at night and the challenges of managing base-loaded unit shut down for short periods during low-load hours is a major problem**

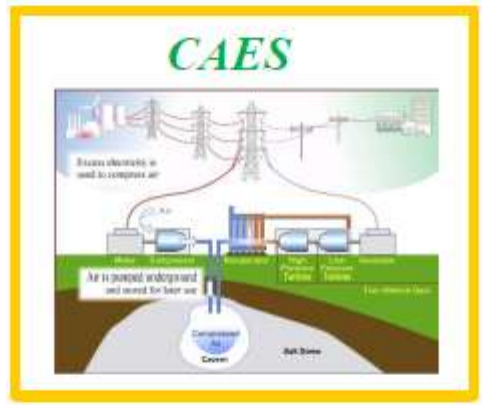
TAKING ADVANTAGE OF INTEGRATED STORAGE RESOURCES

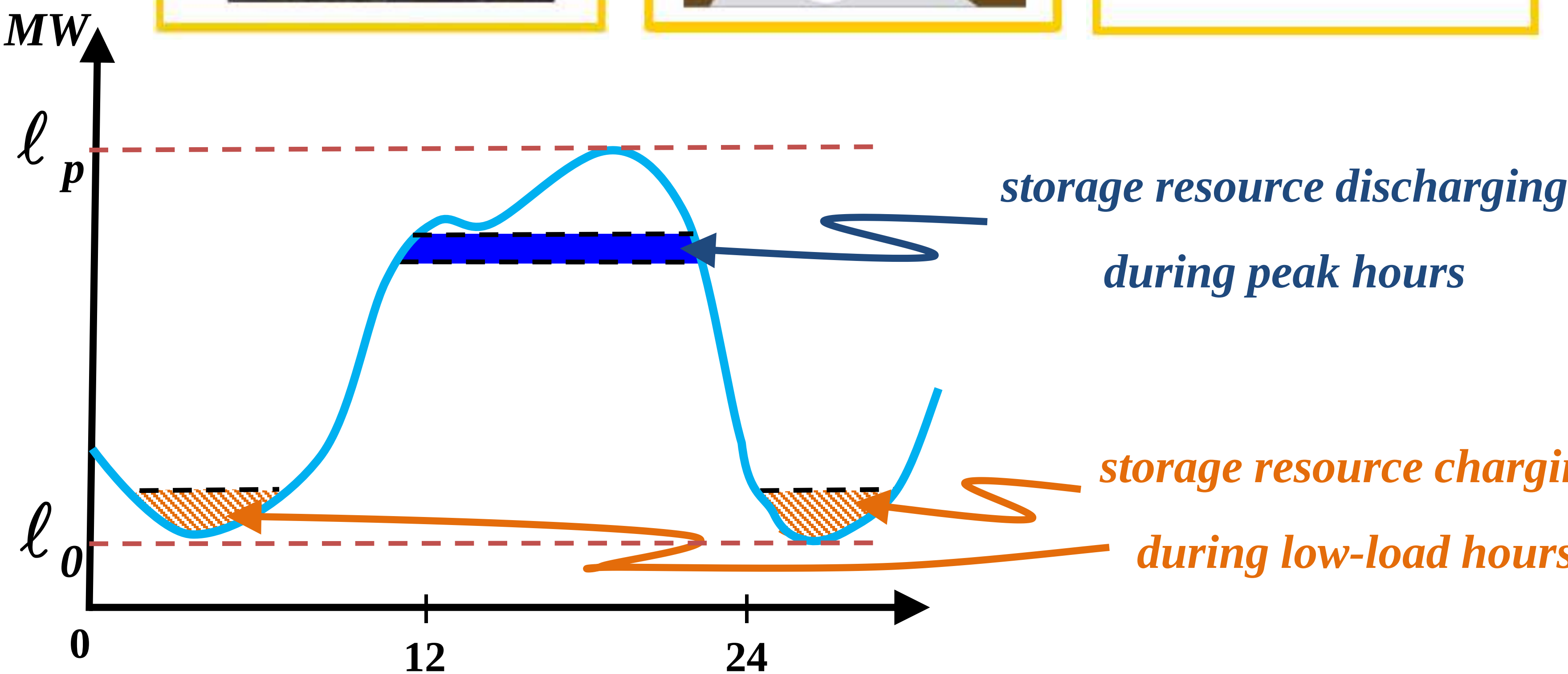
- **In order to take advantage of the increased flexibility imparted by the grid-integrated storage devices, we developed appropriate models, methodologies and tools**
- **The resulting approach has applications to:**
  - **planning and investment analysis;**
  - **policy analysis;**
  - **operations; and**
  - **market performance**

UTILITY – SCALE STORAGE CHARACTERISTICS

- A storage unit may act as either
  - a generating unit; or
  - a load; or
  - is idle – neither as a load nor as a generator
- Storage unit operations are driven by the other resources and so
  - storage is a highly time-dependent resource
  - storage operations are uncertain due to its dependence on other uncertain resources
- Exploitation of arbitrage opportunities in the determination of storage operations is critical

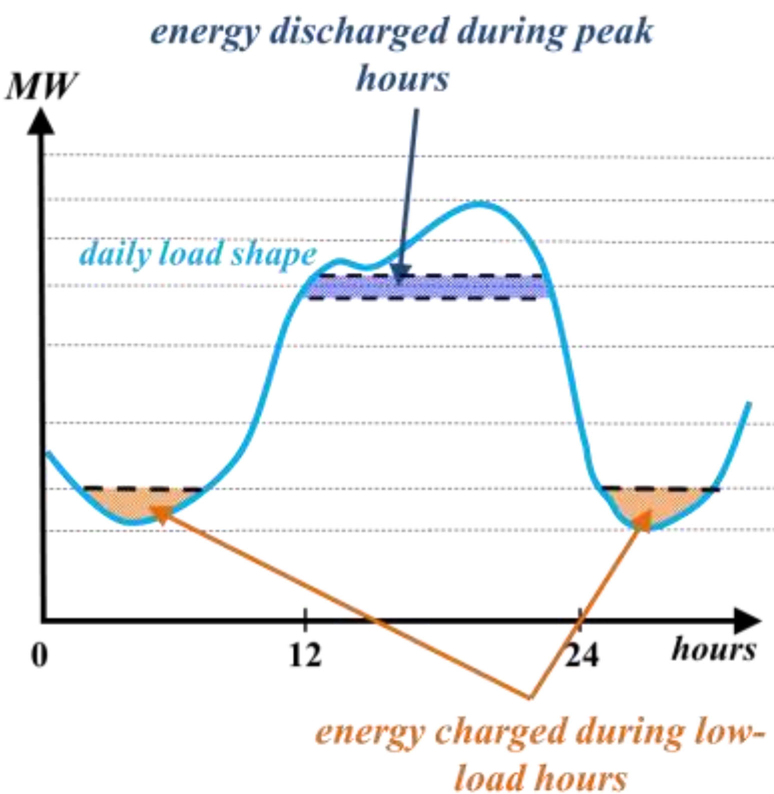
UTILITY – SCALE STORAGE APPLICATION



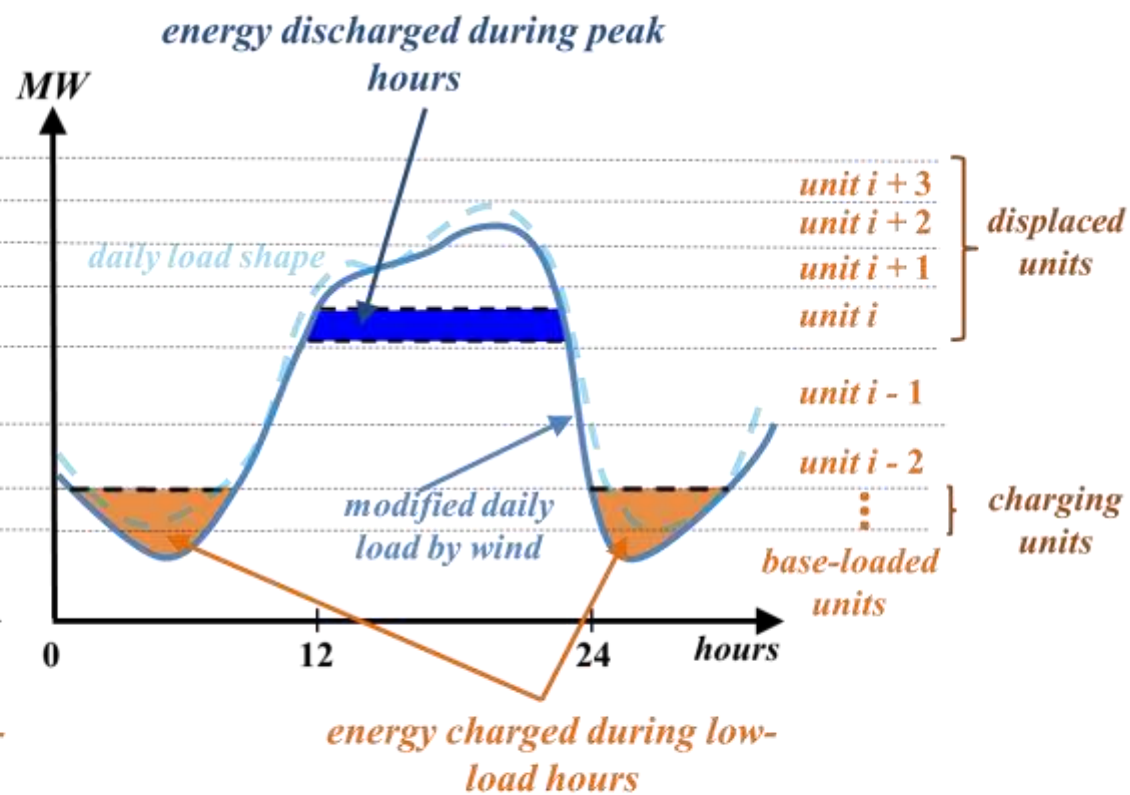


WIND/STORAGE INTERACTIONS

no wind resources



with wind resources



THE NEED FOR A NEW SIMULATION APPROACH

- **The detailed simulation of integrated storage, wind, solar and active demand response resources requires the representation of the time–dependent operational actions in line with the market results**
- **Uncertainties in the loads, wind and solar outputs and conventional unit available capacities requires their explicit representation together with their time–varying nature**

NEED TO EXPLICITLY REPRESENT

- **The loads and their associated uncertainty**
- **The resources and their associated uncertainty:**
  - **conventional generators**
  - **utility-scale storage units**
  - **renewable resources**
- **The spatial and temporal correlations among the resources at the various sites and the loads**
- **The impacts of the grid constraints**
- **The hourly day-ahead markets (*DAMs*)**

THRUST OF THE APPROACH

- We develop a comprehensive, computationally efficient *Monte Carlo simulation* approach to emulate the behavior of the power system with integrated storage and renewable energy resources
- We model the system load and the resources by *discrete-time stochastic processes*
- We deploy the *storage scheduler* to utilize arbitrage opportunities in the storage unit operations
- We emulate the *transmission-constrained hourly day-ahead markets (DAMs)* to determine the power system operations in a competitive environment

THRUST OF THE APPROACH

- We construct appropriate *c.d.f.* approximations to evaluate the expected system variable effects
- Metrics we evaluate include:
  - nodal electricity prices (*LMP*s)
  - generation by resource and revenues
  - congestion rents
  - CO_2 emissions
  - *LOLP* and *EUE* system reliability indices

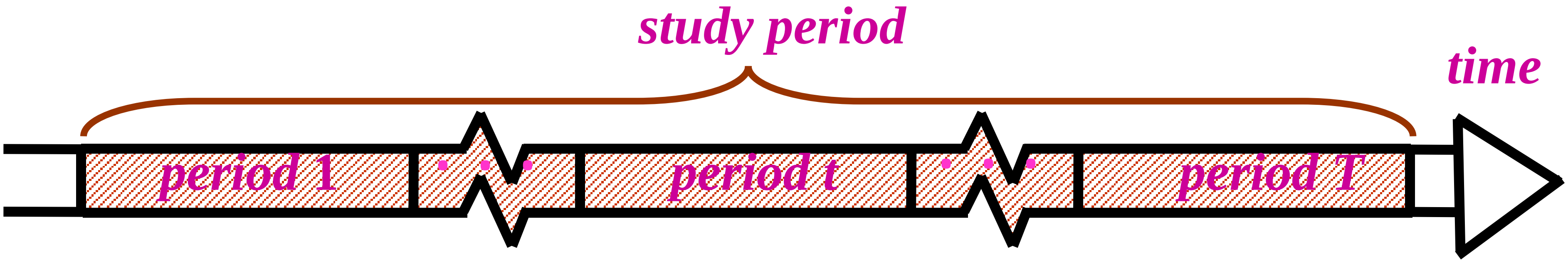
KEY STUDY CONTRIBUTIONS

- Development of a new simulation tool appropriate to address today's power industry challenges
- Salient features include:
  - quantification of the power system expected variable effects – economics, reliability and environmental impacts – in each sub-period
  - computationally tractable for practical systems

STUDY CONTRIBUTIONS

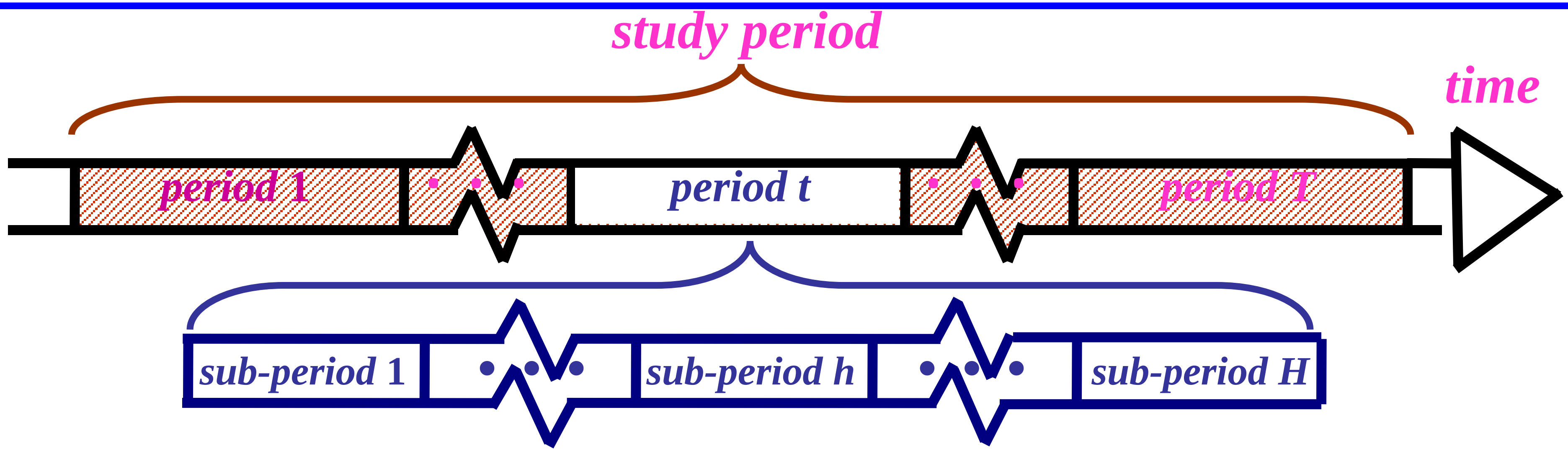
- detailed stochastic models of the time–varying resources and loads allow the representation of spatial and temporal correlations
- storage scheduler for optimized storage operation to exploit arbitrage opportunities
- representation of the transmission–constrained market outcomes
- flexibility in the representation of the market environment / policies

THE TIME DIMENSION IN SIMULATION STUDIES



- We decompose a multi-year study period into *T* non-overlapping *simulation periods*
- We specify the simulation periods in such a way that no changes in the resource mix, unit commitment, the transmission grid and the policy environment occur during each simulation period; such changes may occur in subsequent periods

THE SUBPERIODS: THE SMALLEST INDECOMPOSABLE UNITS OF TIME

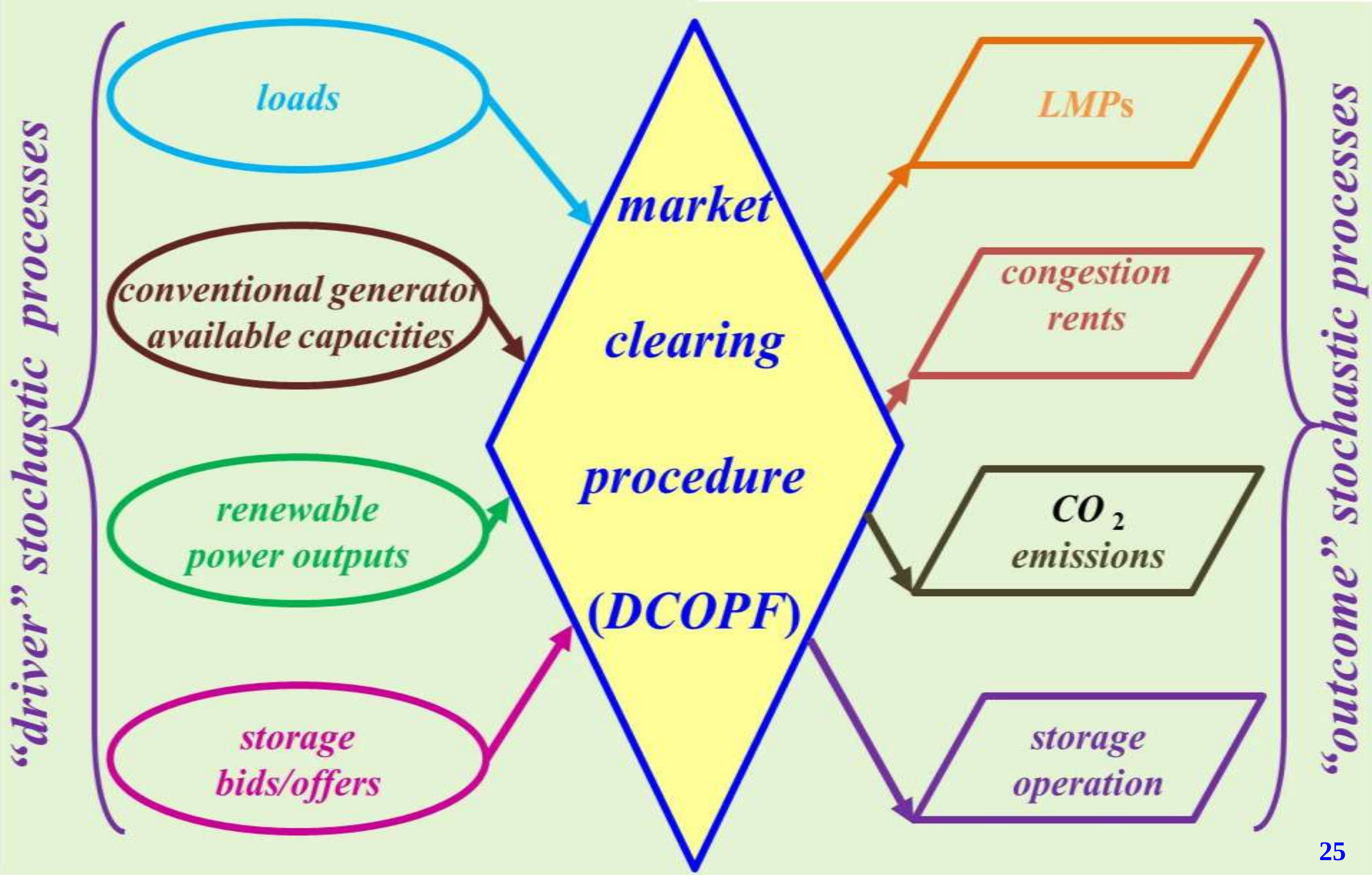


- We introduce sub-periods to explicitly represent the time dependence of the side-by-side power system and market operations
- We use *hourly* sub-periods in the simulation and no phenomena of shorter duration are represented

THE SIMULATION APPROACH: KEY ASSUMPTIONS

- **The system is in the "steady state" for each sub-period and we ignore shorter duration phenomena**
- **The behavior of each market participant is independent of that of the other participants and no participant engages in strategic behavior**
- **The grid is lossless and the *DC power flow conditions* hold over the entire study period**

PROPOSED SIMULATION APPROACH: CONCEPTUAL STRUCTURE



QUANTIFICATION OF SYSTEM VARIABLE EFFECTS

- **We use the approximations to the joint *c.d.f.*s of the market outcome *stochastic processes* to compute the expected values of the system variable effects in each sub-period**
- **In this way, we evaluate all the figures of merit of interest, including expected electricity payments, expected energy supplied by each resource, reliability indices and expected emissions**

ENSURING NUMERICAL TRACTABILITY

- **We introduce various schemes to reduce the computing burden to ensure tractability**
- **Key implementational aspects:**
  - **selection of a group of** ***representative weeks***
  - **variance reduction techniques:** ***stratification*****,** ***control variates*** **and** ***common random numbers***
  - ***warm-start*** **of the linear program solver**
  - ***parallelization*** **of simulation runs**

TYPICAL APPLICATIONS

- Resource planning studies
- Production costing issues
- Transmission utilization issues
- Environmental assessments
- Reliability analysis
- Investment analysis

CASE STUDIES

MOTIVATION

- We present case studies aimed at illustrating the various capabilities of the simulation approach and relevant to the integration of storage and renewable resources
- We perform sensitivity studies to investigate several aspects of storage integration into the grid, notably its impact in a system with deepening wind penetration, its siting, and to what extent storage and renewable resources may replace conventional generation

CASE STUDIES

We present 3 sets of representative case studies:

- **case study set I: impacts of an integrated utility-scale storage unit under a deepening wind penetration scenario**
- **case study set II: siting of 4 energy storage units and the impacts on transmission usage**
- **case study set III: substitution of conventional generation resources by a combination of storage and wind energy resources**

CASE STUDY SET I: DEEPENING WIND PENETRATION

- The objective of this study is to perform a wind penetration sensitivity analysis and to quantify the enhanced ability to harness wind resources with the addition of a storage energy resource
- We evaluate the key metrics for variable effect assessment, including wholesale purchase payments, reliability indices and CO_2 emissions

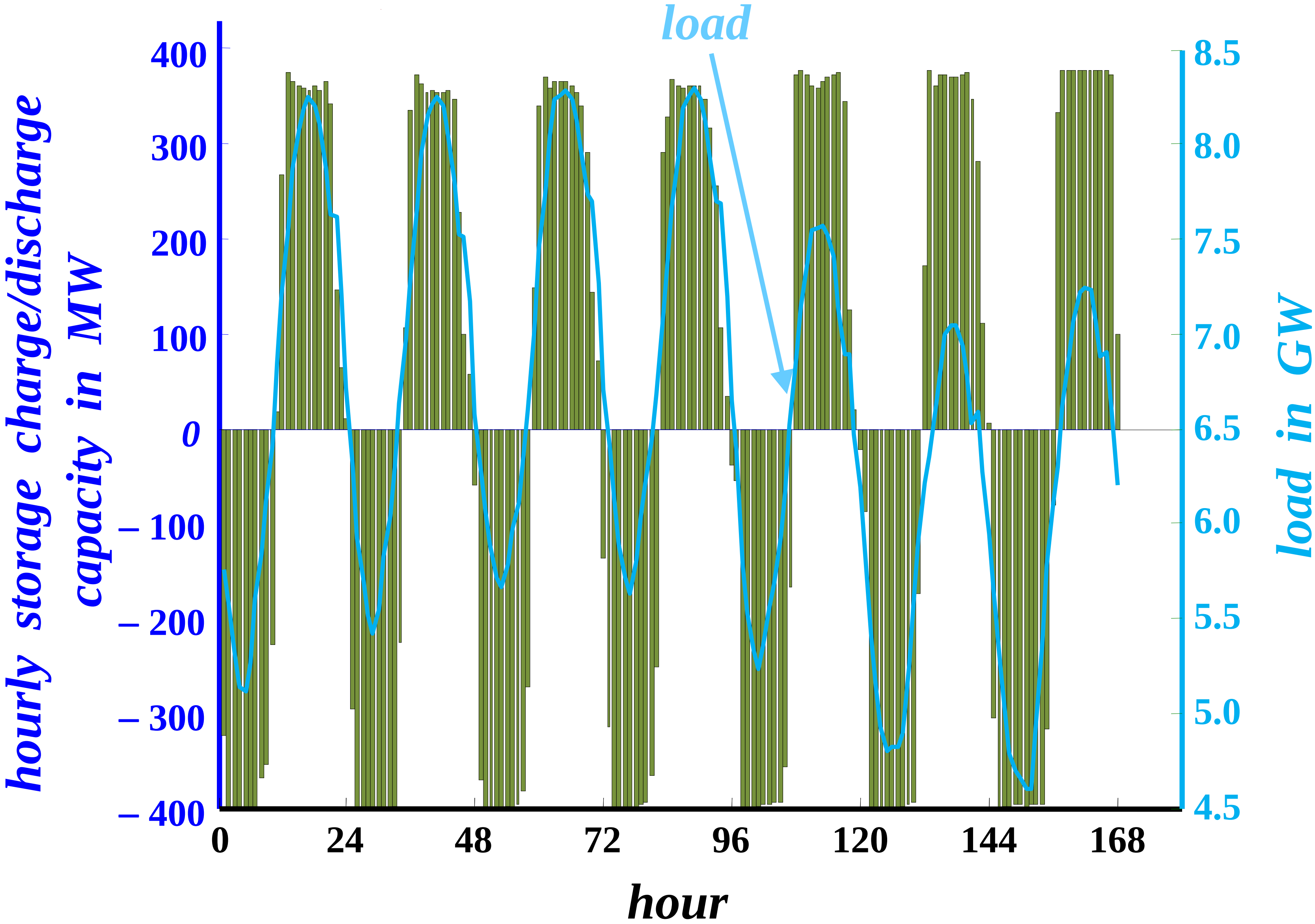
THE STUDY TEST SYSTEM: A MODIFIED IEEE 118-BUS SYSTEM

- **Annual peak load: 8,090.3 *MW***
- **Conventional generation resource mix: 9,714 *MW***
- **4 wind farms located in the Midwest with total nameplate capacity in multiples of 680 *MW***
- **A storage unit with 400 *MW* capacity, 5,000 *MWh* storage capability and 89 % round-trip efficiency**
- **Unit commitment uses a 15 % *reserves margin* provided by conventional units *and the storage resources***

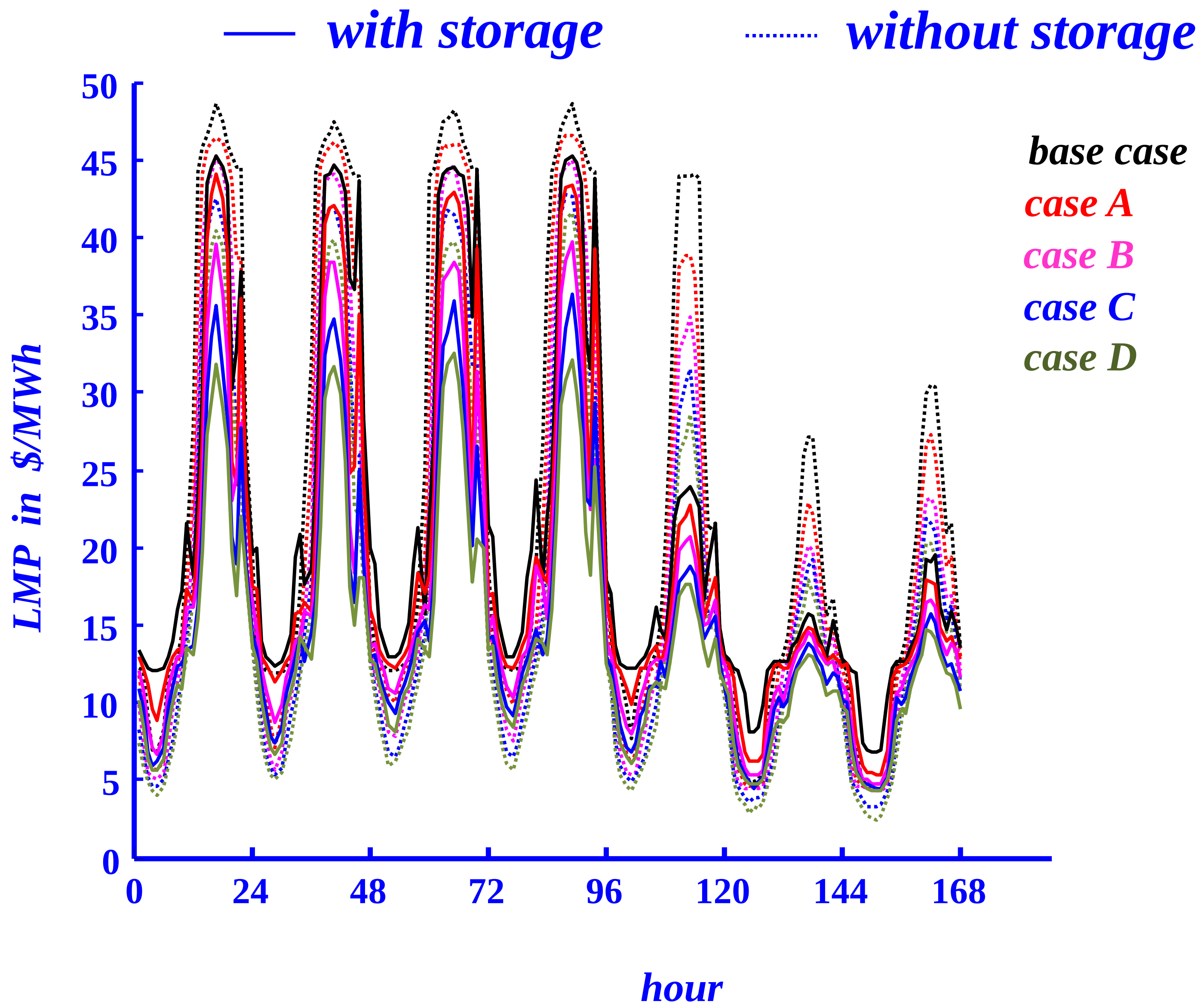
SENSITIVITY CASES IN STUDY SET I

case	*total installed wind nameplate capacity in MW*
base	***0***
A	**680**
B	**1,360**
C	**2,040**
D	**2,720**

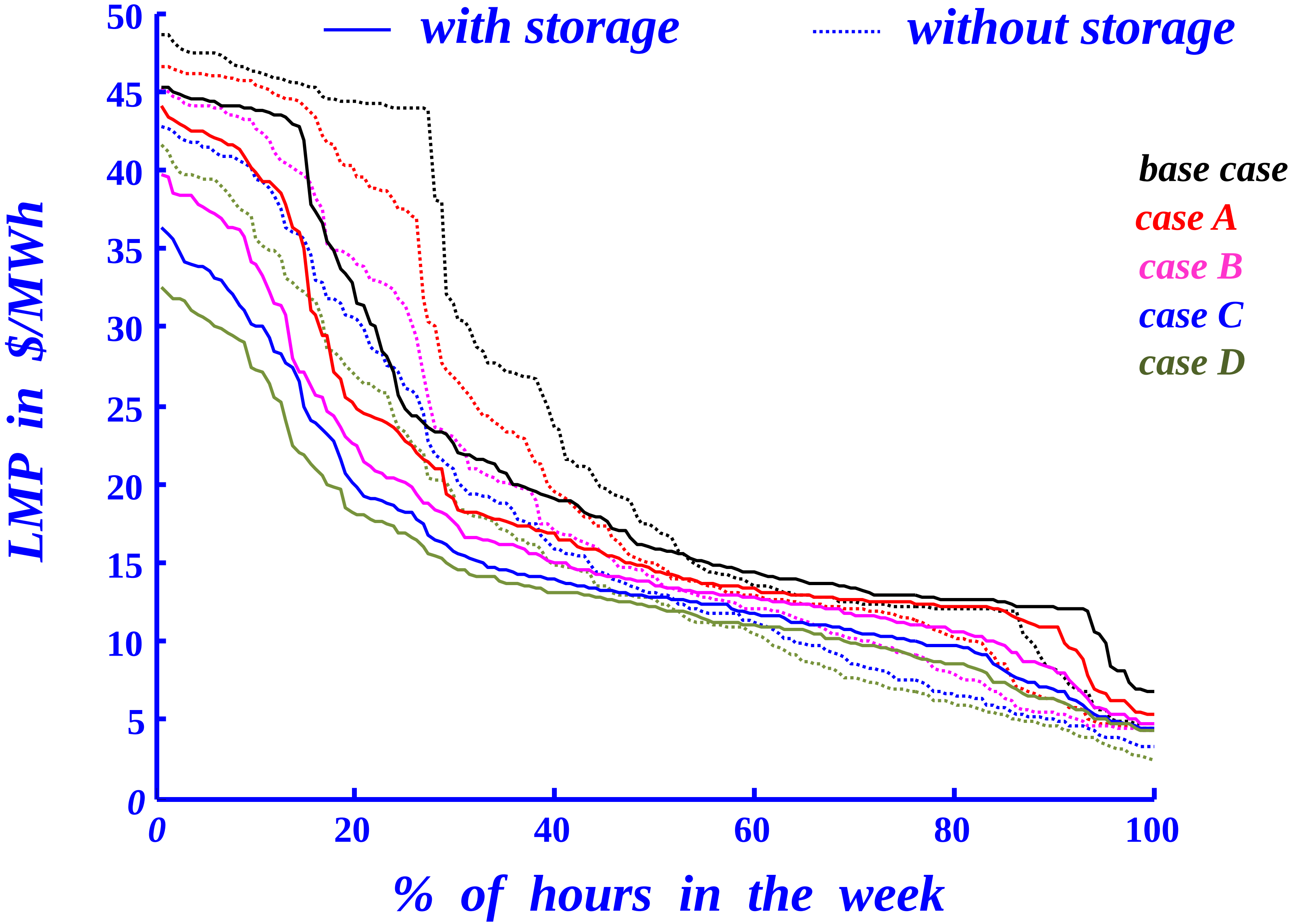
CASE *D*: AVERAGE HOURLY STORAGE UTILIZATION



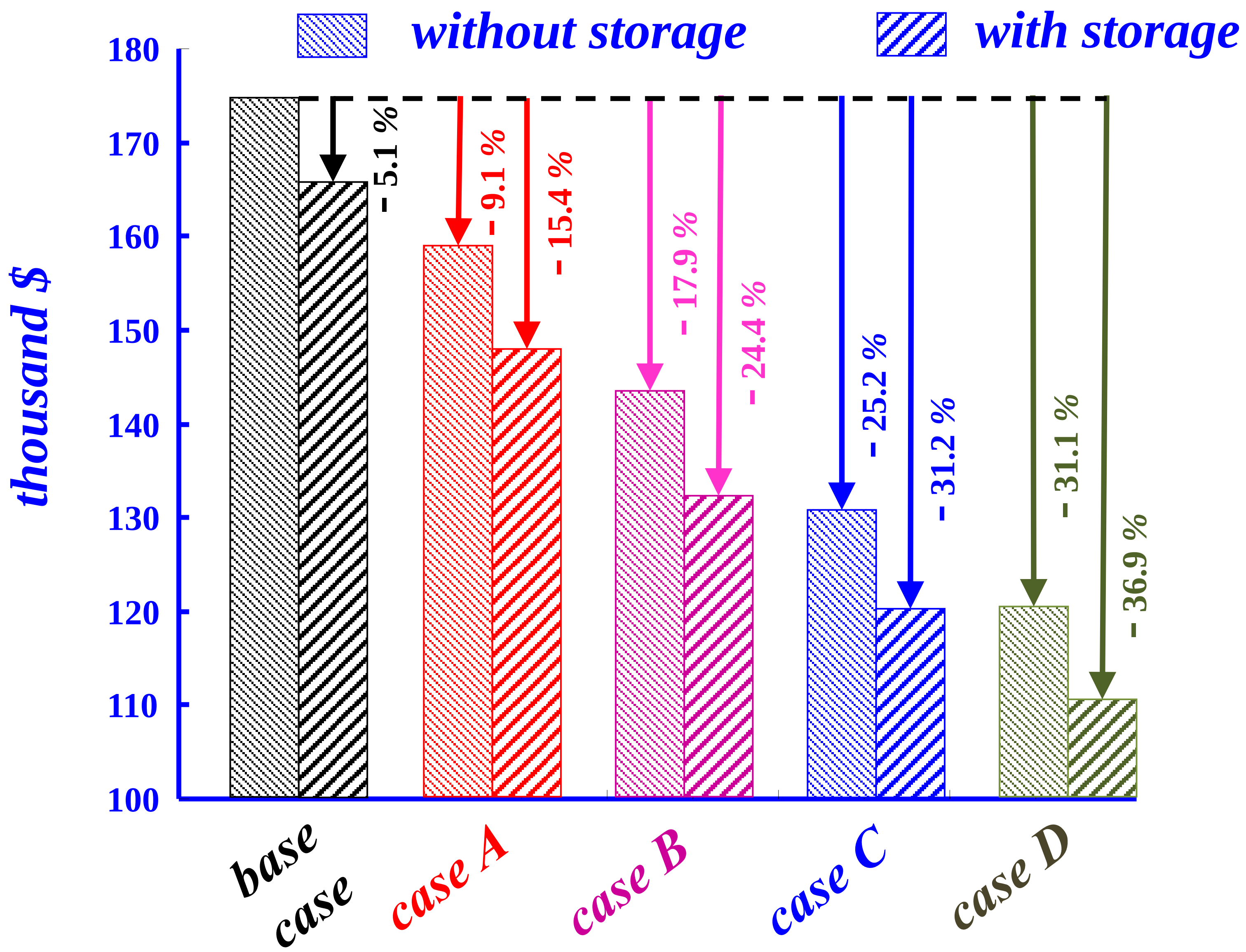
NODE 80 AVERAGE HOURLY *LMPs*



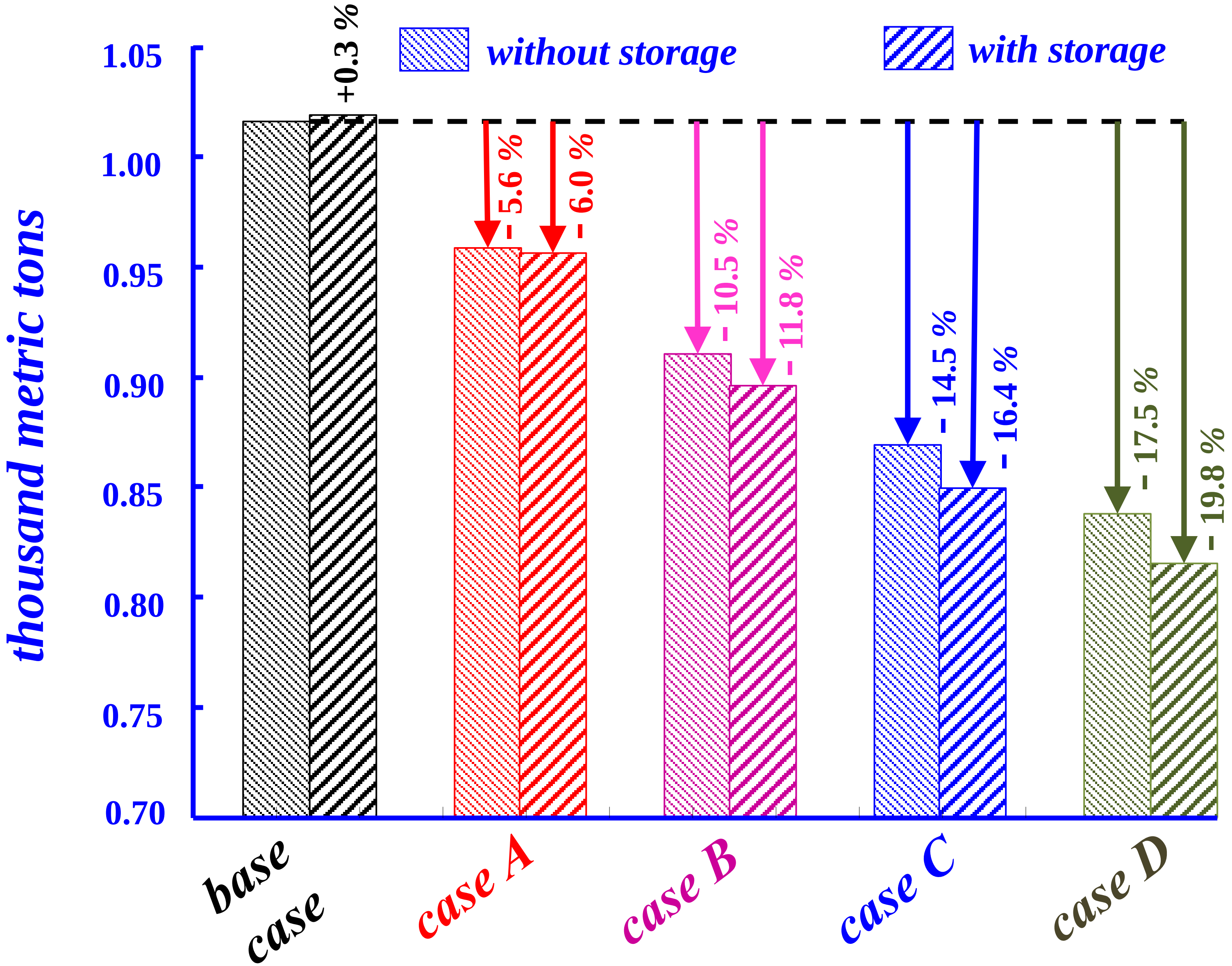
BUS 80 AVERAGE HOURLY *LMP* DURATION CURVE



EXPECTED WHOLESALE PURCHASE PAYMENTS

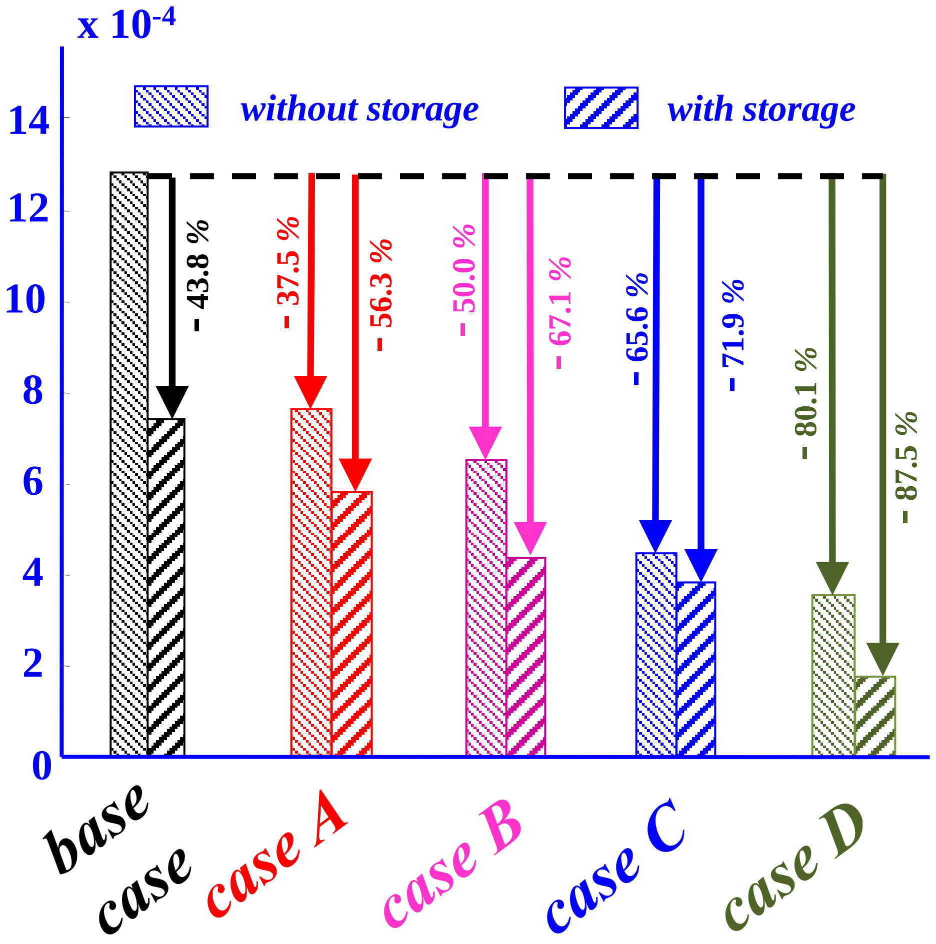


EXPECTED CO_2 EMISSIONS

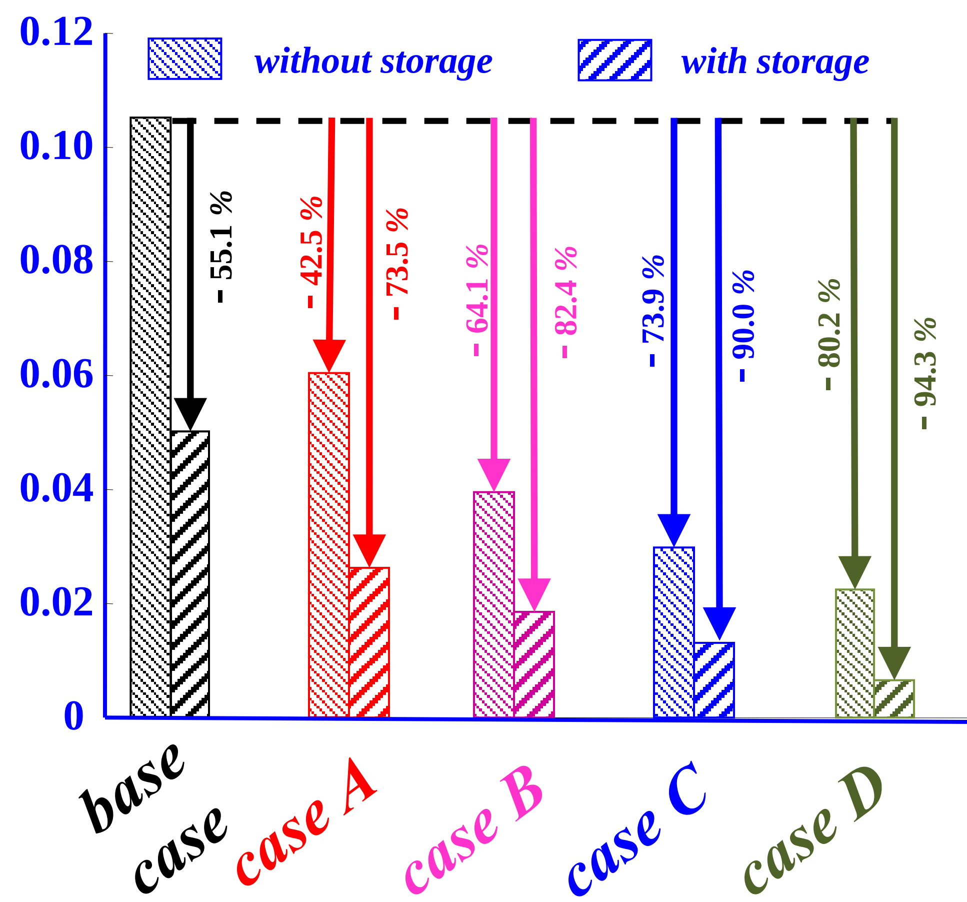


ANNUAL RELIABILITY INDICES

LOLP



EUE



CASE STUDY SET II: STORAGE UNIT SITING

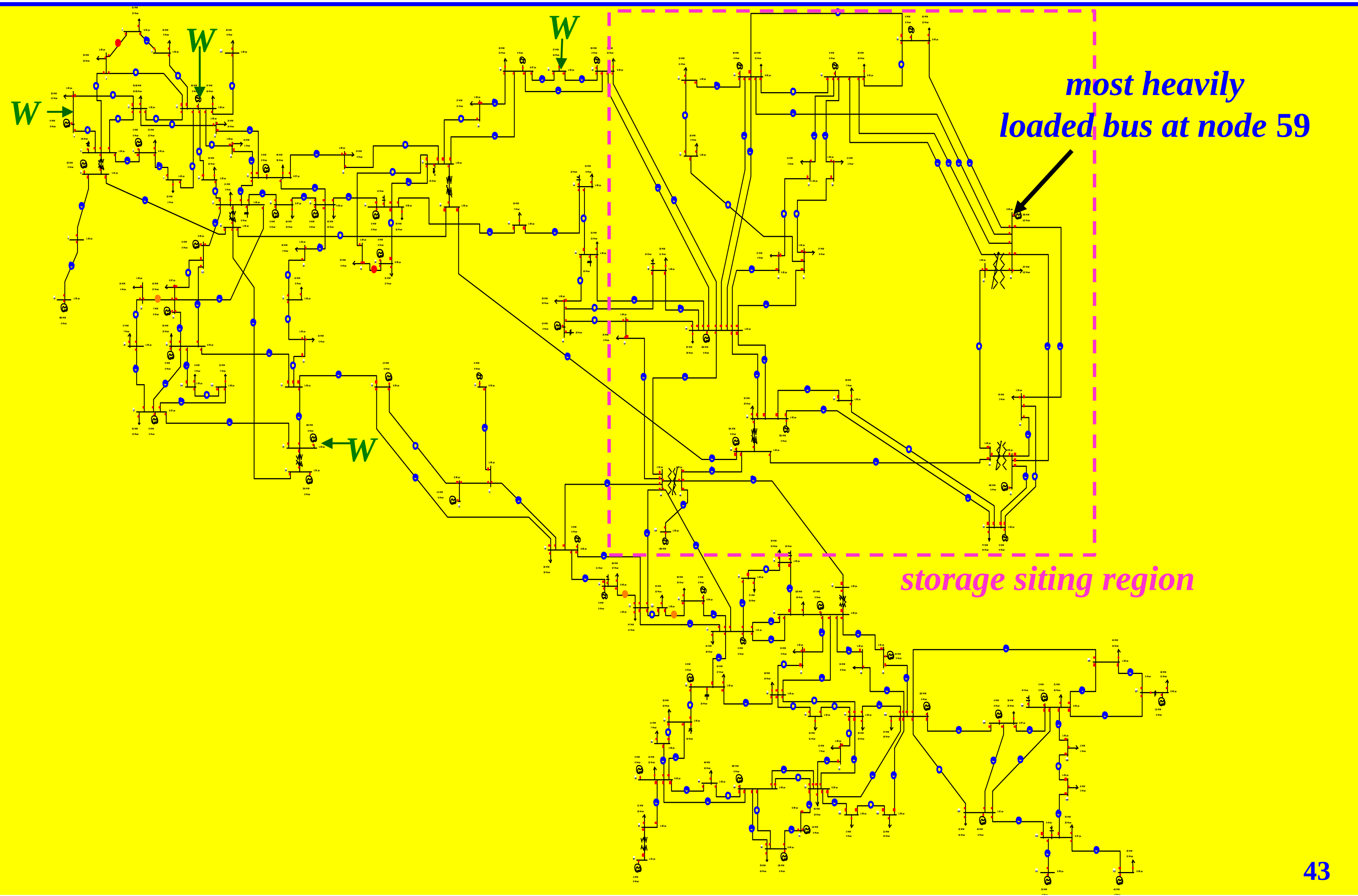
- **The objective of this study is to perform a sensitivity analysis on the siting of 4 storage units in the system and assess its impacts on transmission usage and on the economics at the most heavily loaded bus in the network**

- **We quantify the expected *LMP*s at the load center at node 59 and the total congestion rents**

TEST SYSTEM OF THE STUDY: A MODIFIED IEEE 118-BUS SYSTEM

- **Annual peak load: 8,090.3 *MW***
- **Conventional generation resource mix: 9,714 *MW***
- **4 wind farms located in the Midwest with total nameplate capacity 2,720 *MW***
- **4 identical utility-scale storage units, each having 200 *MW* capacity, 5,000 *MWh* storage capability and 89% round-trip efficiency**
- **Reserves margin is set at 15 % and is provided by conventional *and storage* resources**

STORAGE SITING ON THE MODIFIED IEEE 118 – BUS TEST SYSTEM

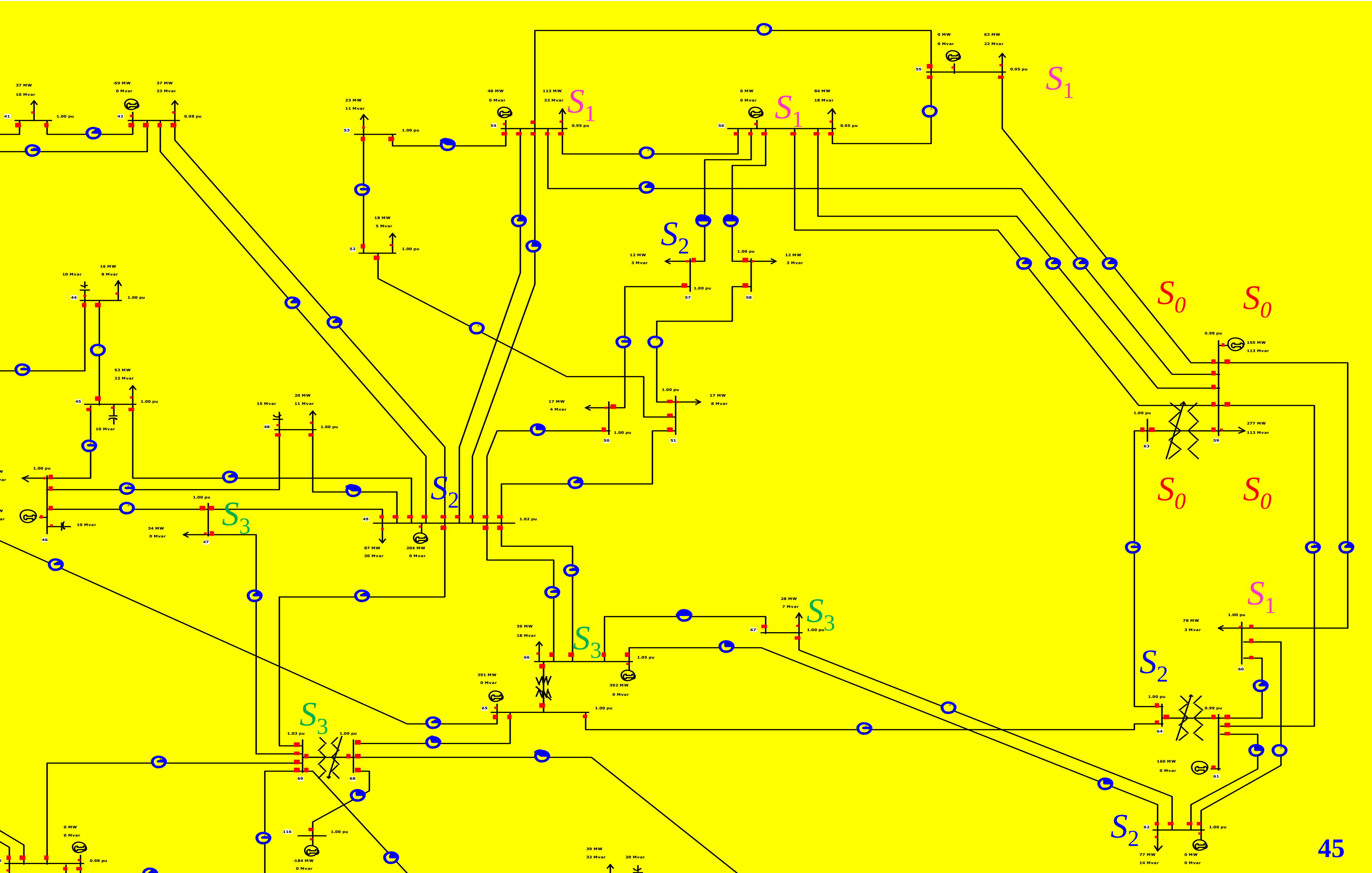


SENSITIVITY CASES IN STUDY SET II

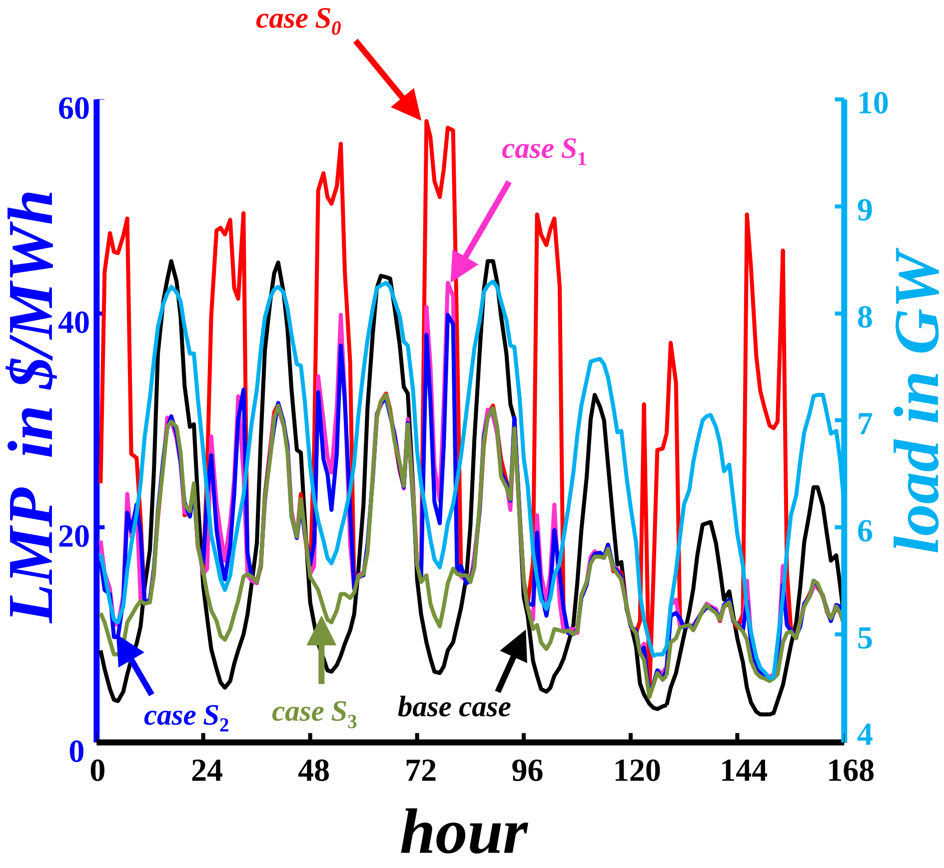
case	*siting of the storage units*
base	*no storage units*
S_0	*at the principal load center*
S_1	1 *node away*
S_2	2 *nodes away*
S_3	3 *nodes away*

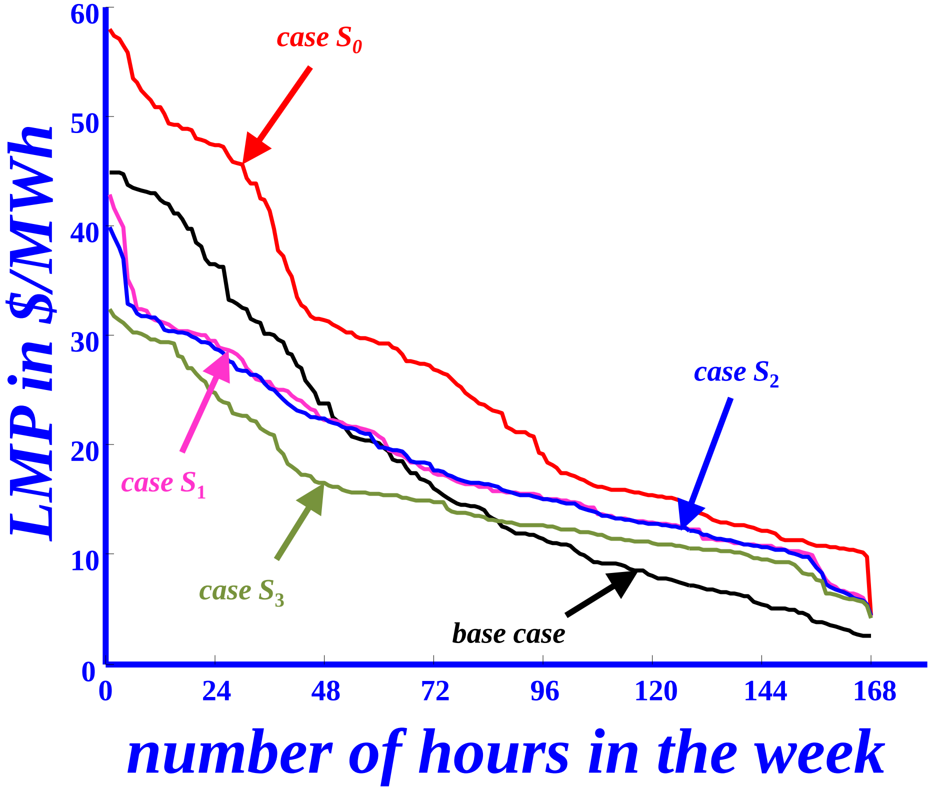
each case has 2,040 *MW nameplate wind capacity*

STORAGE SITING REGION

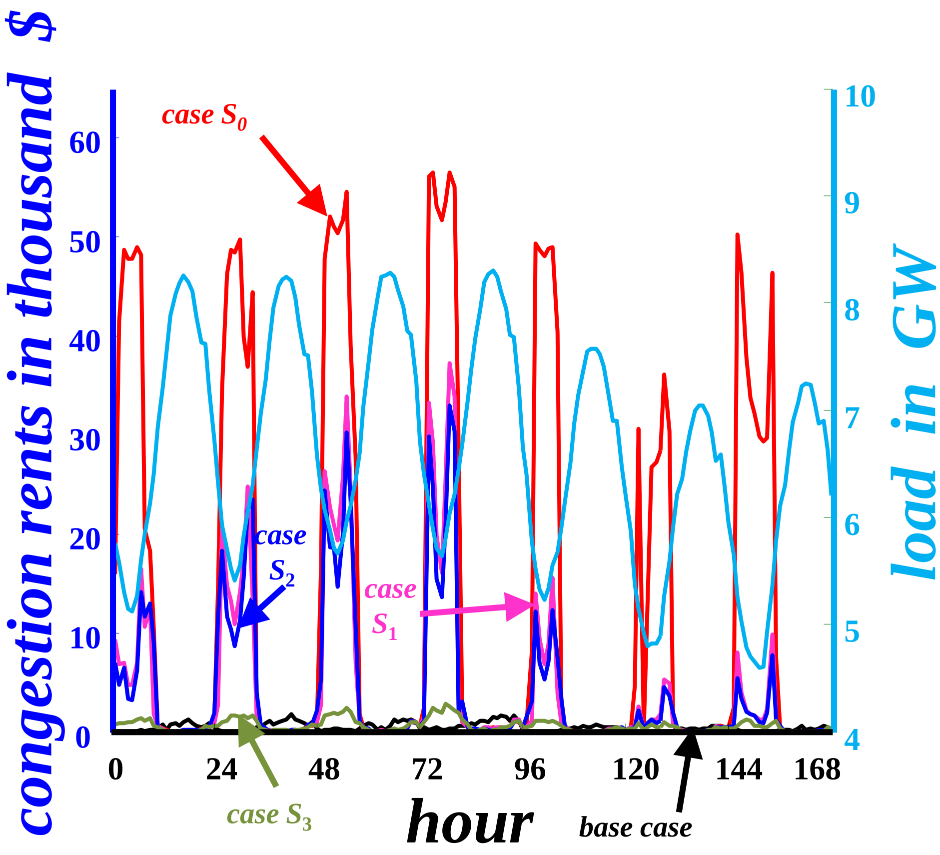


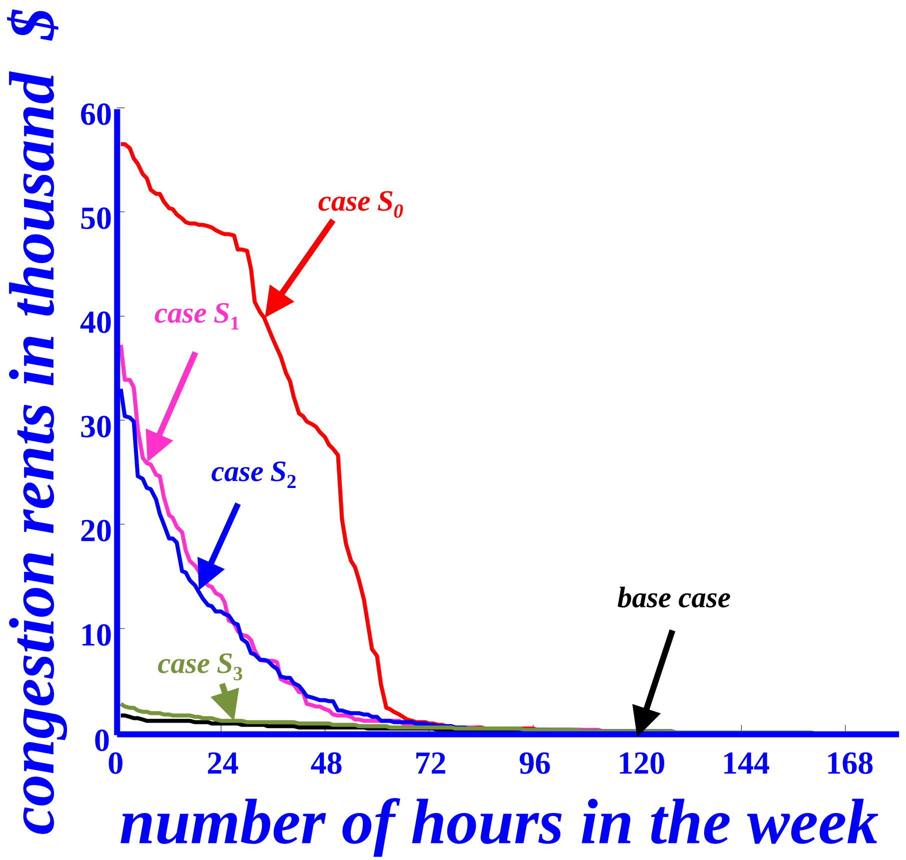
NODE 59 EXPECTED HOURLY *LMPs*



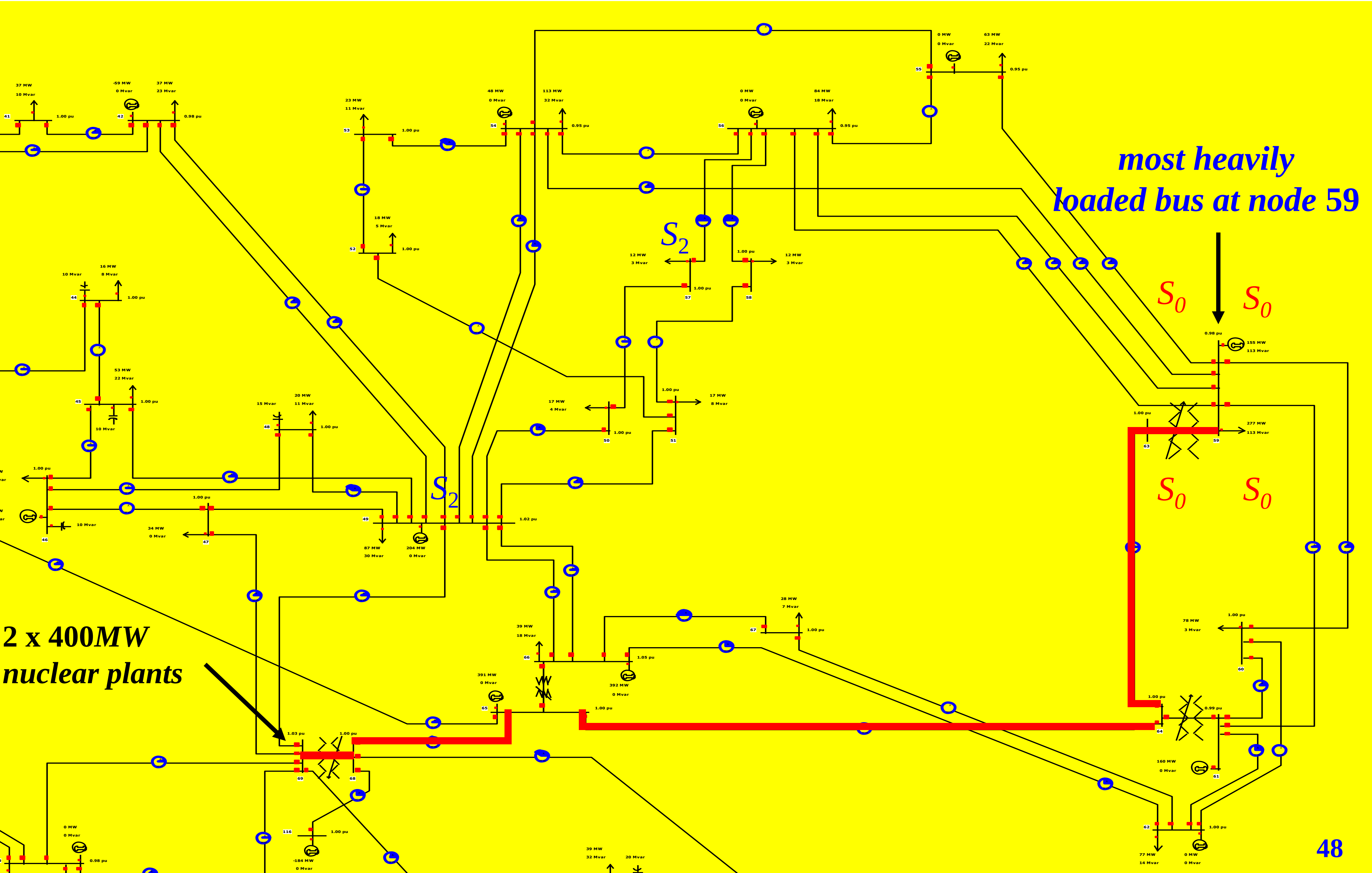


EXPECTED HOURLY CONGESTION RENTS



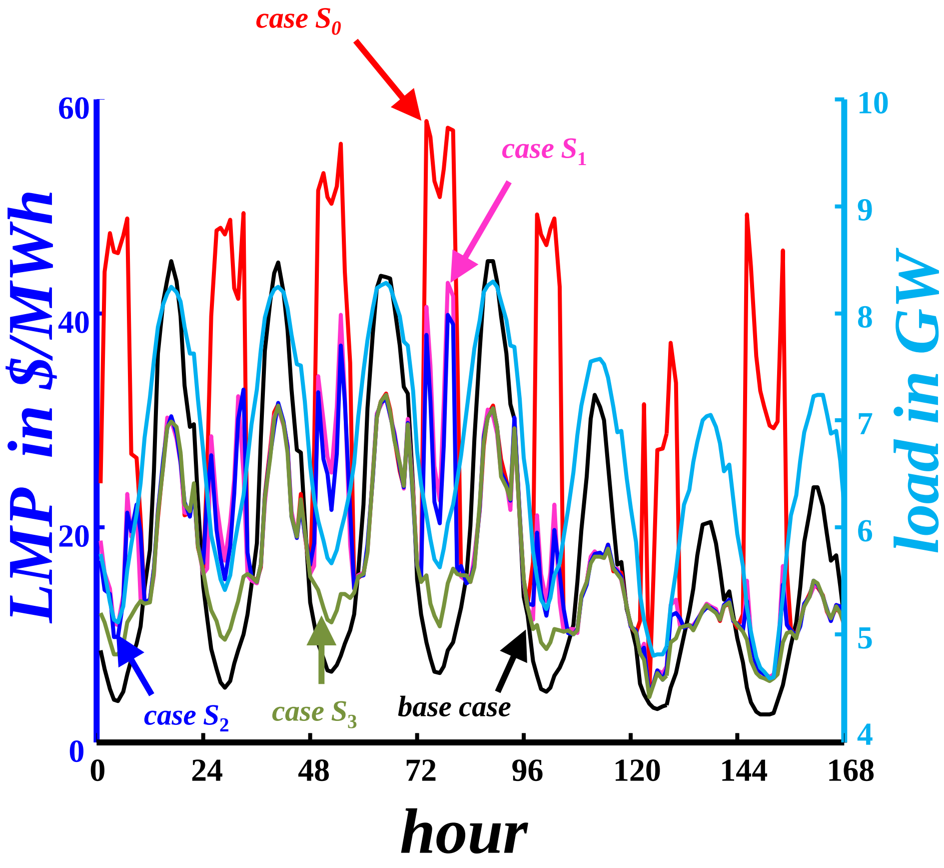


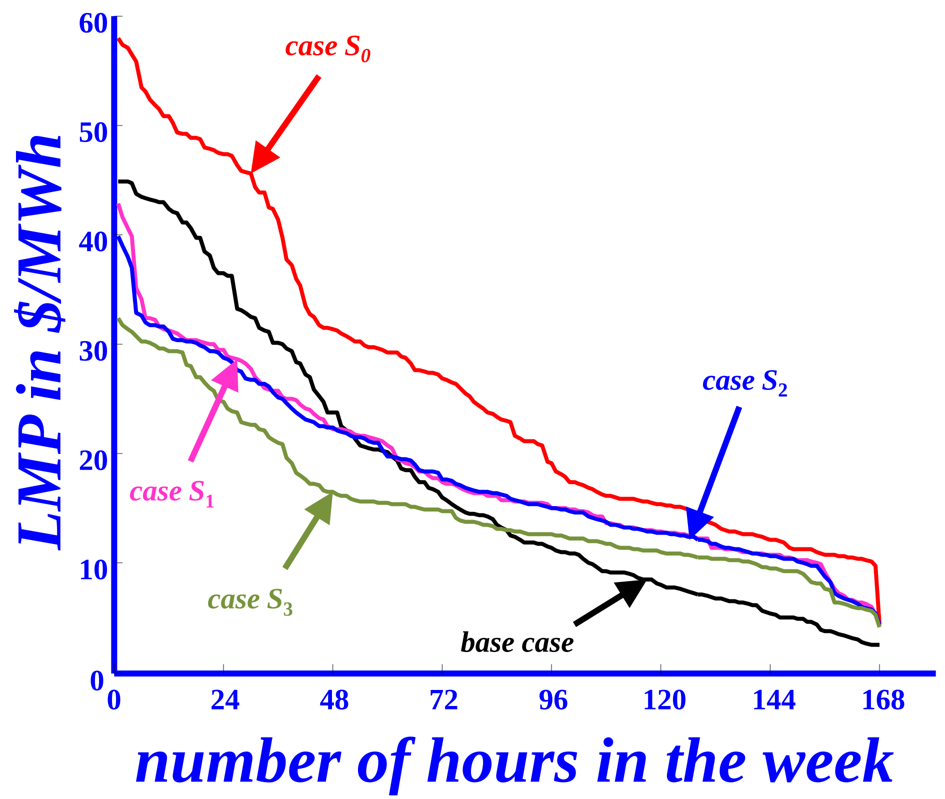
TRANSMISSION PATH CONGESTION AND ITS REENFORCEMENT



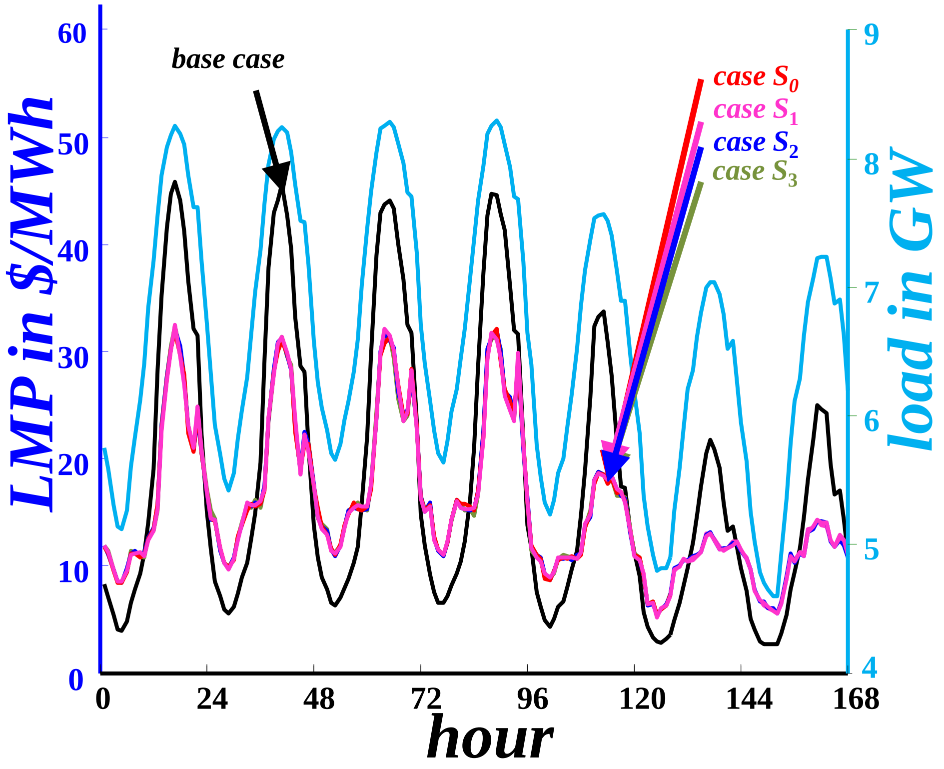
PRE – PATH – REENFORCEMENT NODE 59

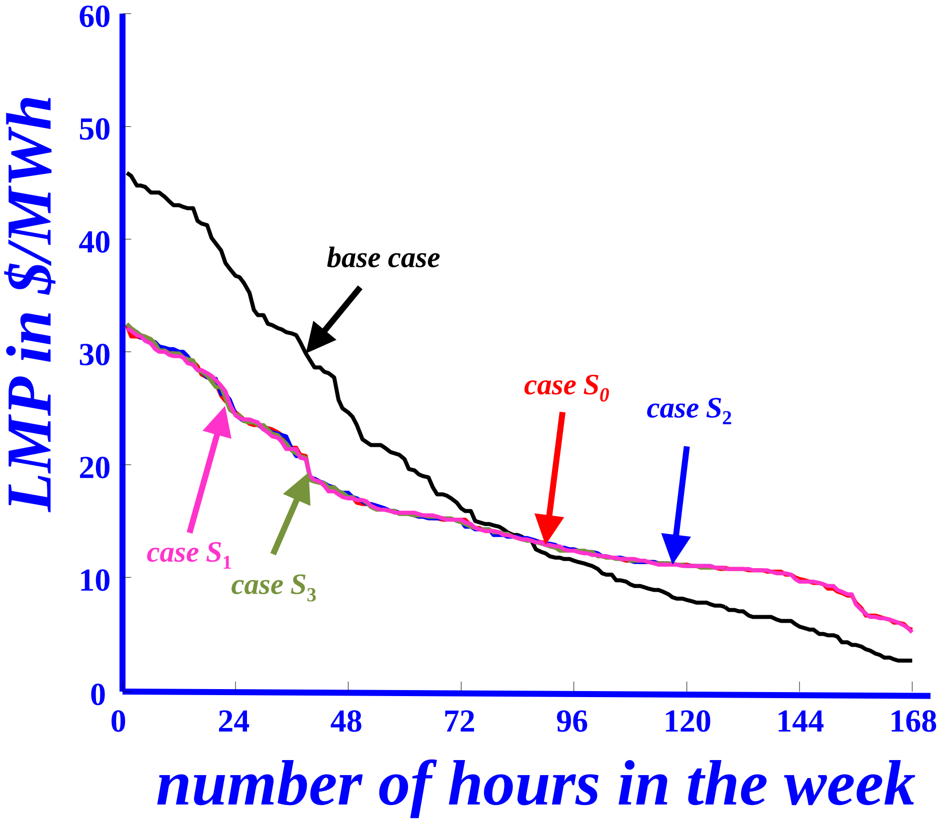
AVERAGE HOURLY LMPs





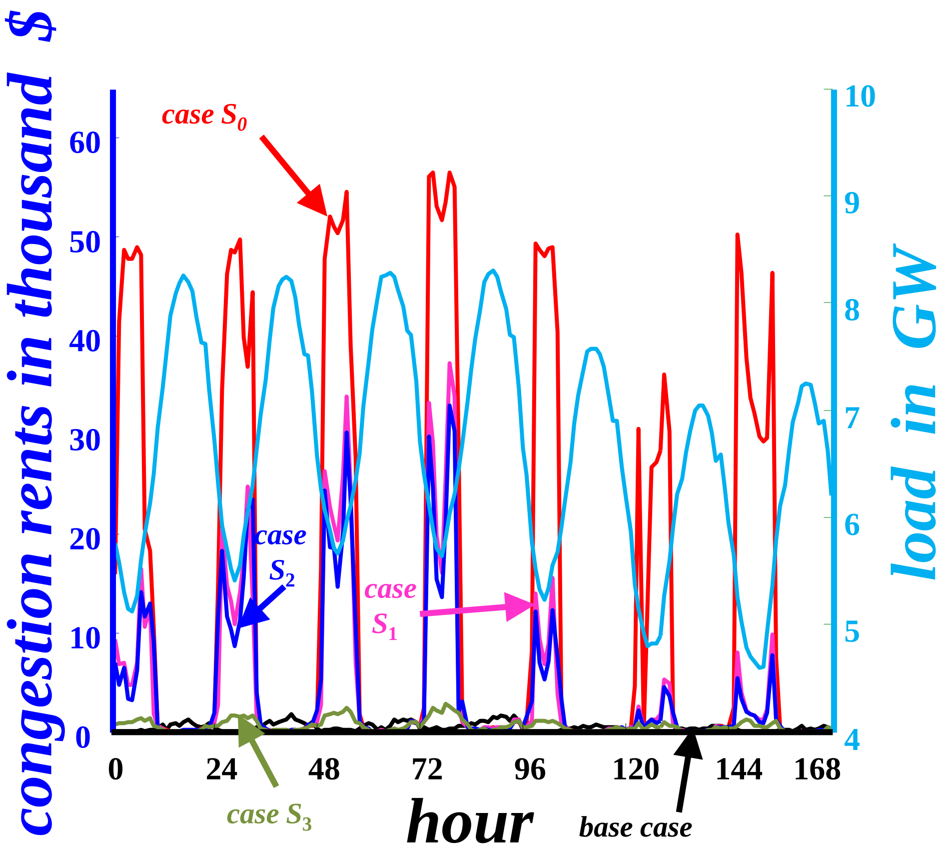
POST – PATH – REENFORCEMENT NODE 59
AVERAGE HOURLY LMPs

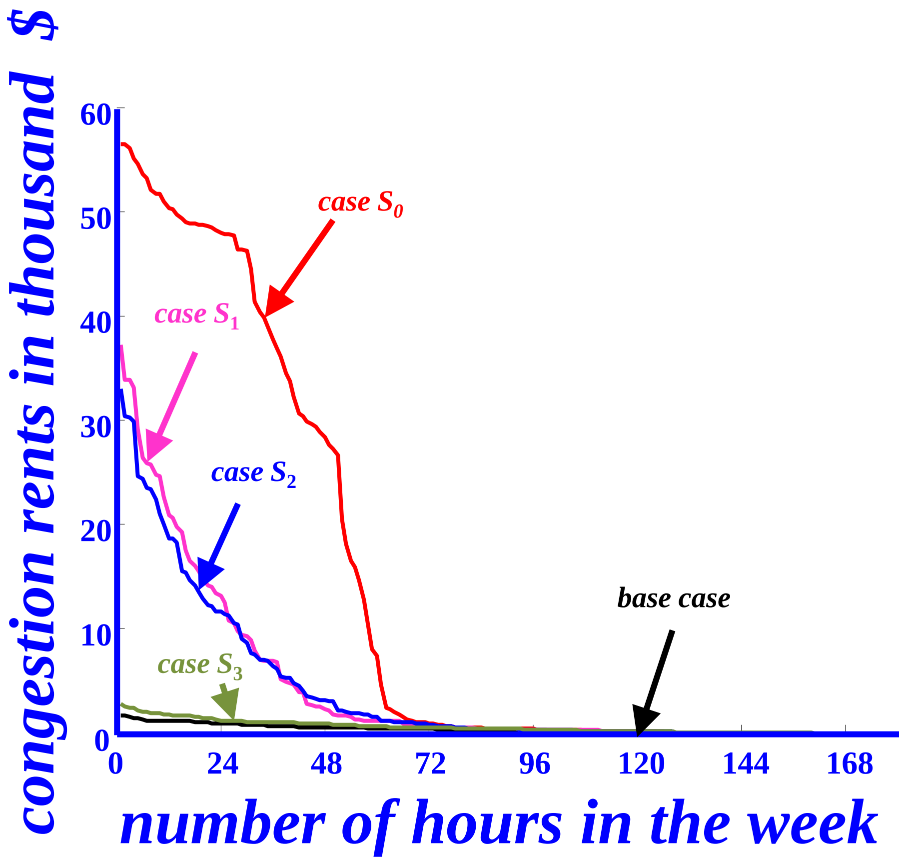




PRE – PATH – REENFORCEMENT

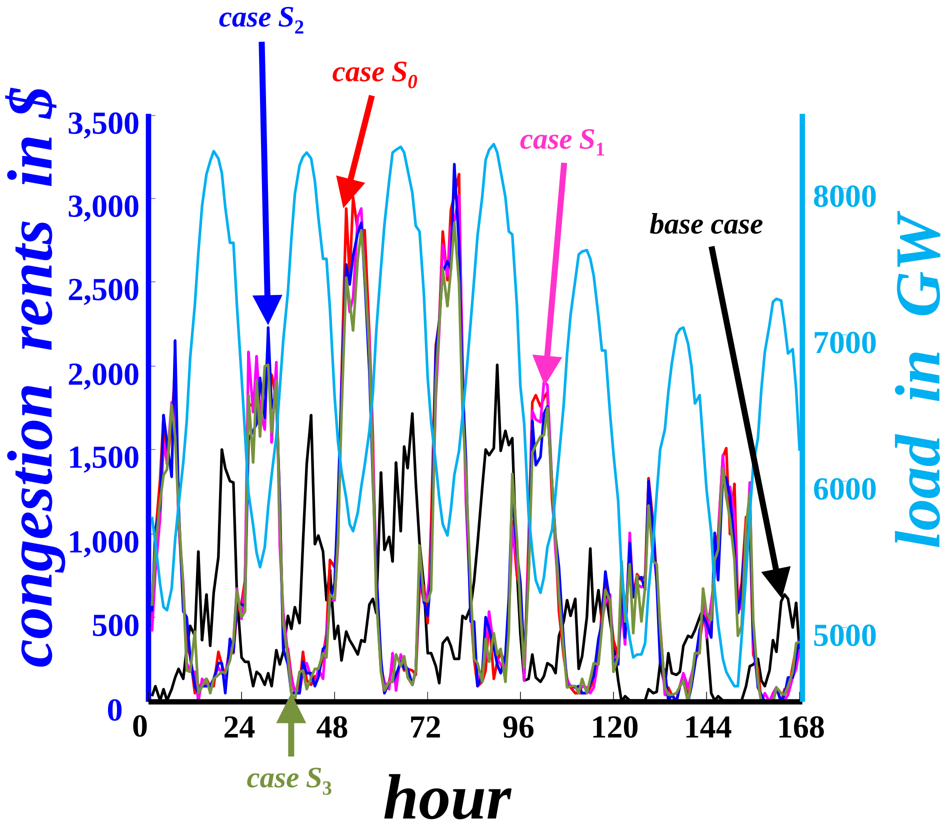
AVERAGE HOURLY CONGESTION RENTS

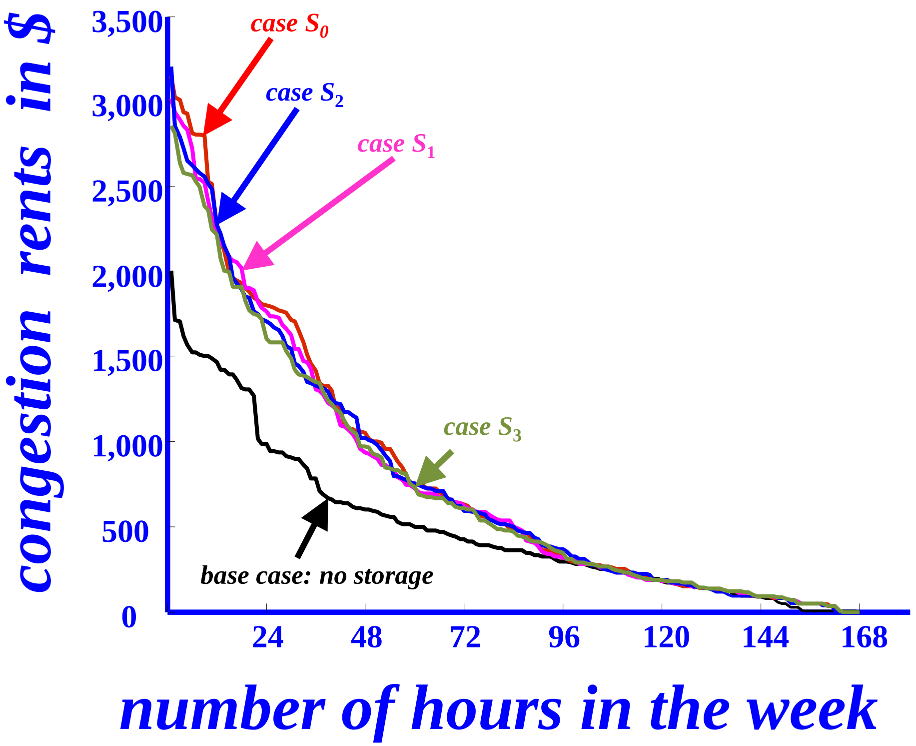




POST – PATH – REENFORCEMENT

AVERAGE HOURLY CONGESTION RENTS





STUDY SET III: SUBSTITUTION OF THE CONVENTIONAL RESOURCES

- The aim of this study is to quantify the extent, from a purely reliability perspective, wind resources can substitute for conventional generation capacity in a power system with integrated storage resources
- We deem storage units to be firm capacity and use them to meet the desired reserves margin
- As the wind resources are integrated, we decrease progressively the system reserves margin, retire conventional unit capacity and assess the impacts

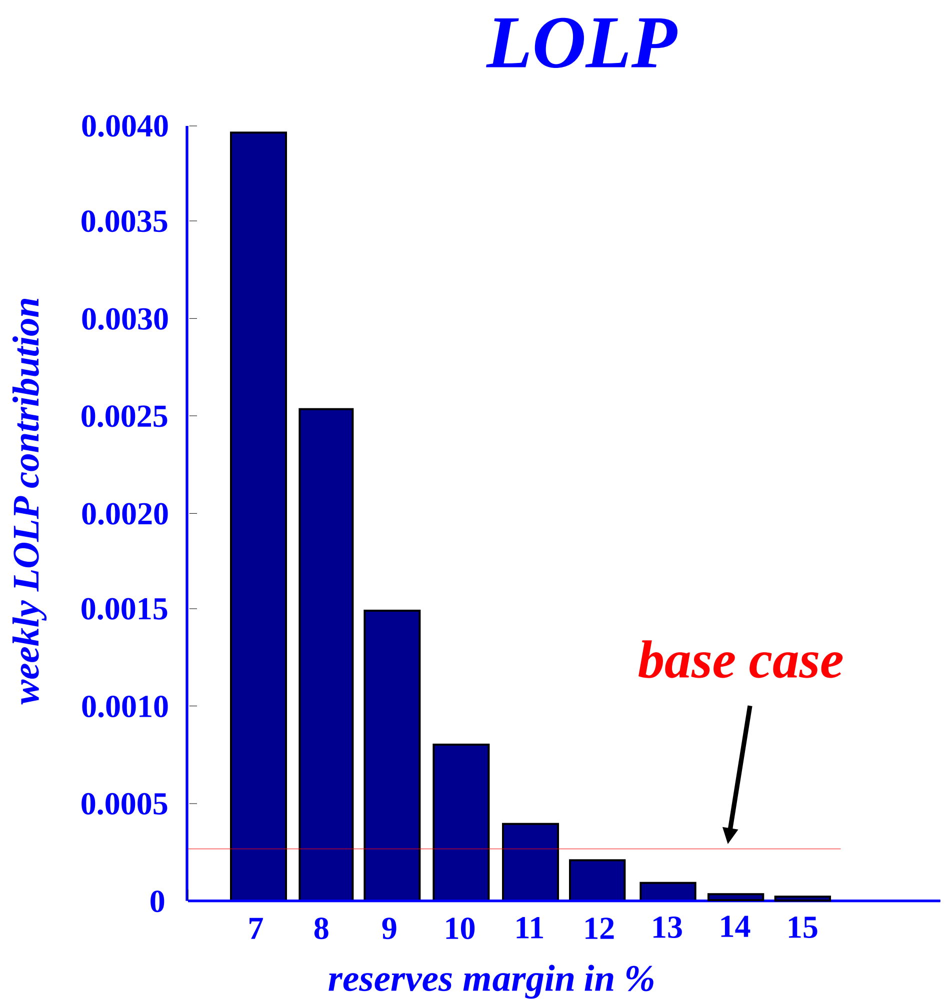
THE STUDY TEST SYSTEM: A MODIFIED IEEE 118-BUS SYSTEM

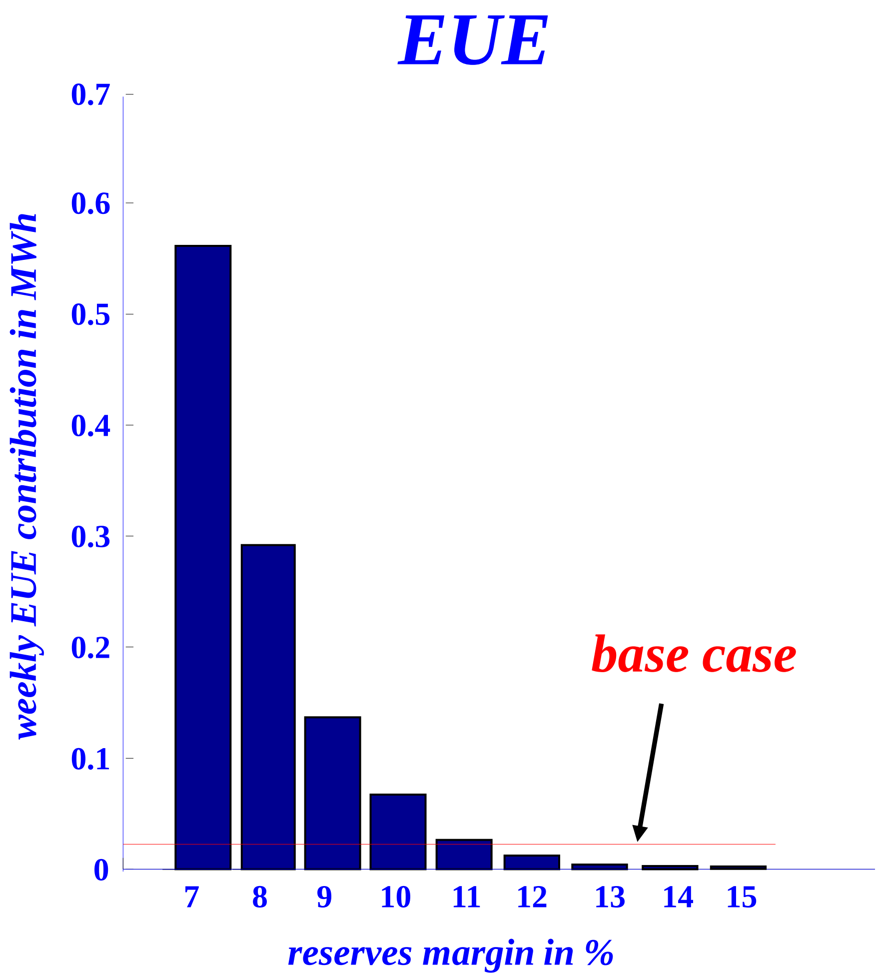
- Annual peak load: 8,090.3 *MW*
- Conventional generation resource mix: 9,714 *MW*
- 4 wind farms located in the Midwest with total nameplate capacity of 2,720 *MW*
- 4 units: each has a 100 *MW* capacity, 1,000 *MWh* storage capability and 89 *%* round-trip efficiency
- The unit commitment is performed to ensure the desired reserves margin is attained from the conventional *and storage* resources

SET IV SENSITIVITY CASES

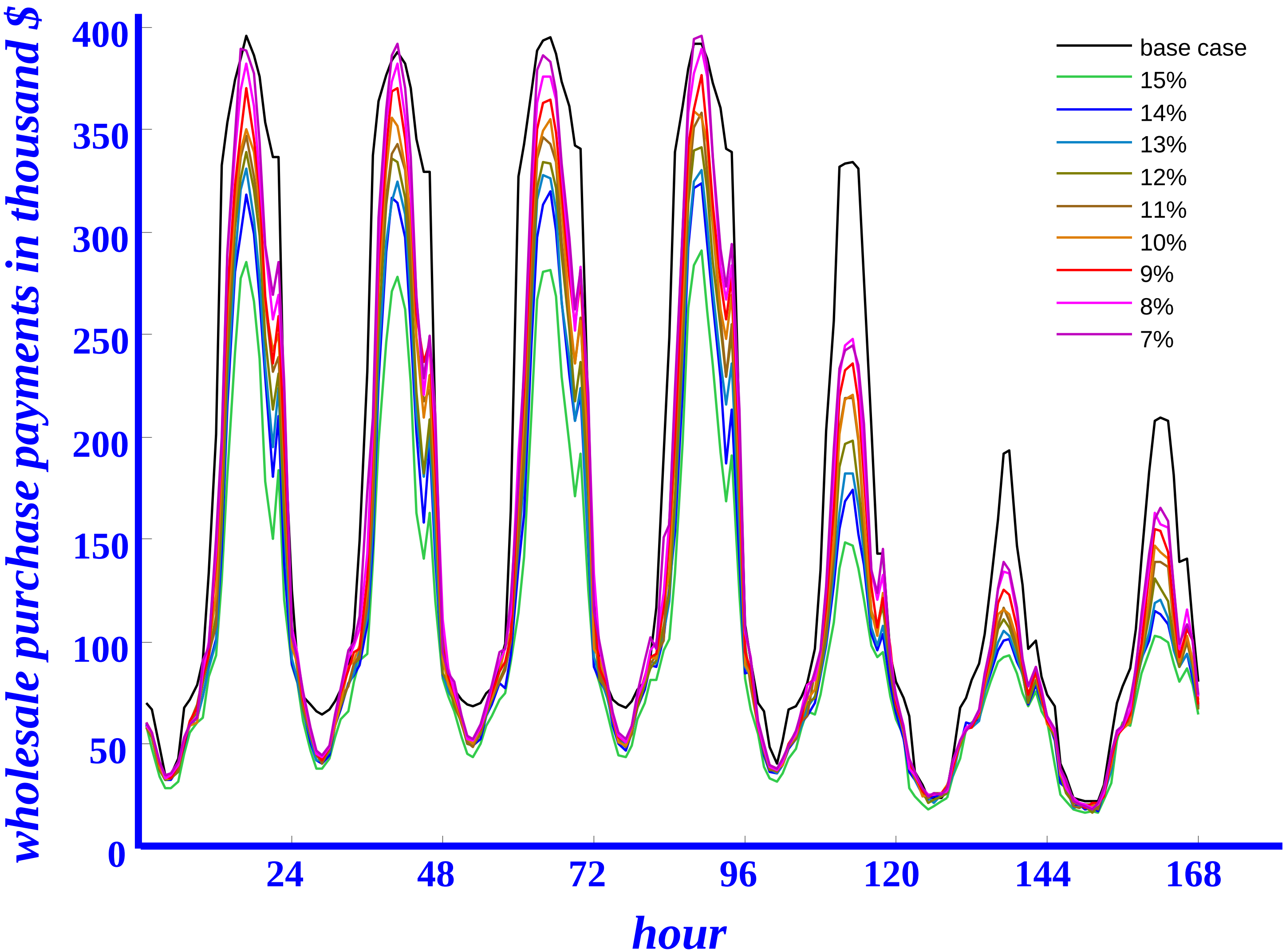
case	*reserves margin in %*
base (no wind, no storage resources)	15
R_0	15
R_1	14
R_2	13
R_3	12
R_4	11
R_5	10
R_6	9
R_7	8
R_8	7

WEEKLY RELIABILITY INDICES vs. RESERVES MARGINS





MEAN HOURLY WHOLESALE PURCHASE PAYMENT IMPACTS



KEY FINDINGS OF THE ILLUSTRATIVE STUDIES

- **Deeper penetration of wind resources reduces** ***DAM LMPs*****s, wholesale purchase payments,** CO_2 **emissions and improves system reliability**
- **Storage works in synergy with wind to drive wholesale purchase payments further down and improve system reliability**
- **Overall,** CO_2 **emissions are not significantly affected by the integration of a storage unit**

KEY FINDINGS OF THE CASE STUDIES

- **Storage siting significantly impacts the congestion rents and the *LMP*s at certain nodes**
- **In a system whose storage resources are used to substitute for conventional generation to meet the desired reserves margin requirements, large amounts of wind capacity are required to replace the retired conventional generation capacity: in the case studies presented the 2,720 *MW* of wind can substitute for about 300 *MW* of retired conventional generation capacity – about 3.7 % of peak load**

KEY FINDINGS OF THE CASE STUDIES

- Absent storage units, with all other conditions remaining unchanged, the 2,720 MW wind can replace only about 220 MW of retired conventional generation capacity – about 2.7 % of peak load
- We attain significant reductions in wholesale purchase payments – about 25 % – when storage and wind resources substitute for conventional resource capacity with the same reliability level

SUMMARY OF PROJECT CONTRIBUTIONS

- Development of a practically-oriented approach to simulate large-scale systems over longer-term periods
- Comprehensive and versatile approach to quantify the impacts of the integration of storage devices into power systems with deepening penetration of renewable resources
- Demonstration of the capabilities of the proposed approach to a broad range of planning, investment, transmission utilization and policy analysis studies

CONCLUDING REMARKS

- Storage and wind resources consistently pair well together: they reduce wholesale purchase dollars and improve system reliability; storage seems to attenuate the "diminishing returns" trend seen with deeper wind power penetration
- The location of a storage unit can have large local impacts; siting requires case-by-case studies
- Wind resources can substitute for conventional resources to a very limited extent, even in a