RELIABILITY AND SECURITY ISSUES OF MODERN ELECTRIC POWER SYSTEMS WITH HIGH PENETRATION OF RENEWABLE ENERGY SOURCES

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Introduction

- ✓ Future Electric Power Systems must be developed with a target for **Low Emission Energy Performance.**
- ✓ Use of advanced generation technologies that can obtain high conversion efficiency rates.
- ✓ Use of various technologies for power generation from Renewable Energy Sources.
- ✓ Application of appropriate measures for obtaining conservation of electric energy and efficient management of electric power demand.
- ✓ Use of advanced technologies for the development of the Future Transmission Systems.

Introduction

(continue)

✓ Operation of electric power systems by considering various types of conventional generating units, cogeneration units and installations of Renewable Energy Sources (RES):

- Thermal Power Plants (TPP)
- Large Hydroelectric Power Plants (HPP)
- Small Hydroelectric Power Plants (SHPP)
- Power Storage Plants (PSP)
- Wind Parks (WP)
- Photovoltaic Systems (PS) - Solar Thermal Plants (STP)
- Biomass (BI) and Small Cogeneration (CP) Power Plants.

Introduction

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- ✓ High penetration level of RES.
- ✓ Development of a computational methodology for the reliability and operational assessment of power systems:
  - Simulation of power system operation for each hour of a calendar year (8760 hours).
  - Calculation of appropriate indices that quantify the overall reliability and operational performance of the system.
  - Rules of competitive electric energy market.
  - Reliability Criteria for the system operation.
  - Emphasis is given for the environmental performance of the generating plants and the overall system.

Introduction

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- ✓ Stochastic (probabilistic) behaviour is considered that concerns:
  - The operation of the generating units for all types of power plants (failure events, repair duration).
  - Wind power generation (wind speed).
  - Water inflows into the reservoirs of the hydroelectric power plants (rainfalls).
  - Power generation of photovoltaic systems and solar thermal plants irradiation.
  - Uncertainty of predicting system load demand (hourly variations).
- ✓ Analysis of a typical system based on the Hellenic electric power system.

Power System Reliability

It includes:

- ⇨ Adequacy: Ability of the system to satisfy the customer requirements (power, energy) considering the forced outages and the scheduled maintenance outages of system equipment.

- ⇨ Security: Ability of the system to remain in operation after sudden disturbances that may occur (short circuit, loss of equipment, e.t.c.). It may take into account any actions causing such disturbances (human errors, extreme weather conditions, terrorist actions, e.t.c.).

Power System Planning

- Motivated by pressures to reduce emissions, planning efforts increasingly focus on the integration of RES, low-carbon fossil, geothermal and biomass energy sources as well as various types of distributed generation.
- Onshore wind power generation is the most promising RES in areas with high wind potential (relatively inexpensive with short lead times).
- Photovoltaic and Solar thermal plants are of great interest in areas having high solar resources.
- Nuclear technology is not considered although an increased interest has been shown again in recent years while possible accidents constitute the main barrier for developing nuclear power plants (4th generation).

Power System Planning

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- Planning procedures for short decision horizons (5-10 years) determine power system generation needs for satisfying all load conditions and reserve requirements (Reliability Based Planning Approach).
- Planning must take into account the uncertainties being introduced by the market legislation and environmental considerations in order to predict future system conditions and time scales to complete investments.
- Generation issues concerning the commissioning of new and decommissioning of old power plants are now determined outside the system planning arena.
- Generation mix is changing and more intermittent energy sources are connected with lower inertia.

Power System Planning

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- It is difficult to forecast interconnection flows since they are based on market conditions at the respective ends and significant system risks and constraints are created.
- It is necessary to determine a wind generation capacity level above which the power system becomes uncontrollable under certain conditions.
- It is expected that the impact of transmission network failures may become more widespread. All possible technical options must be identified together with the justification of the respective investments to the stake holders.

Wind Power Generation

- ✓ It occurs when wind is blowing with a variable level of power.
- ✓ It is not dispatchable like conventional one and it is primarily an energy resource and not a capacity resource.
- ✓ Its primary value is to contribute for obtaining low emission performance of power systems.
- ✓ Concerns exist about its impact on maintaining system reliability performance and the balance between system load and generation.

Can Power System Operation Handle the Continually Changing Wind Power Generation?

- ✓ Power systems are designed to handle significant variability in loads.
- ✓ Very short – term load changes (seconds to minutes) are small relative to peak load while changes over longer periods (hours) tend to be more correlated.
- ✓ The variability of wind power generation must be managed by system operator.
- ✓ The load net of wind power must be supplied by conventional power plants.
- ✓ At large penetration levels, wind can induce steeper ramps in both directions but its relative variability generally decreases as larger scale geographical aggregation is used for system operation.

Can Power System Operation Handle the Continually Changing Wind Power Generation?

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- ✓ Generating units of conventional power plants must have the required ramping capability.
- ✓ Individual wind parks can have zero power output for many hours (more than 1000) but aggregated wind power generation is nearly always greater than zero.
- ✓ The impact of significant weather events requiring wind turbine shut down for safety reasons is small:
  - not frequent events at large area aggregation
  - sudden interruptions of wind power generation have multi hour downward ramp
  - control systems can be designed to prevent all wind turbines from shutting down during the same minute.

Can Power System Operation Handle the Continually Changing Wind Power Generation?

(continue)

- ✓ Failure events of wind turbines (a few MW) have small impact on system reliability performance in comparison with that of conventional generating units (many MW).
- ✓ Wind power generation can be predicted but the accuracy of the available numerical methods is under discussion (about 20% for day ahead forecasts).

Wind Capacity Credit

- ✓ Traditionally, System planning requires reserves margin equal to 12% - 15% of peak load value (Deterministic method).
- ✓ Probabilistic methods can be used for a more realistic planning by calculating certain reliability indices (LOLE, LOEE) while appropriate targets are specified.
- ✓ As penetration levels of wind power generation increase, its contribution to system adequacy is becoming an important reliability issue.
- ✓ Wind power generation can contribute to the load – carrying capability (Capacity Credit or Value) and its impact can be quantified by calculating the relevant system reliability indices.

Wind Capacity Credit

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- ✓ Various Capacity Credit indices have been proposed but the most important one refers to the capacity of appropriate thermal power plants so that the same system reliability performance is obtained (index LOLE or LOEE).
- ✓ The Capacity Credit is expressed either in MW or as a percentage of the installed wind generation capacity. Available studies have shown that it ranges from 5% to 40%.
- ✓ As penetration levels increase, it increases in absolute terms (MW) but it decreases in relative terms (%).
- ✓ Study in Greece has shown a Capacity Credit of about 20% assuming specific data for wind power generation and thermal power plants of various technologies (i.e. 600MW of CCGT are equivalent to 3000MW of wind parks).

Wind Capacity Credit

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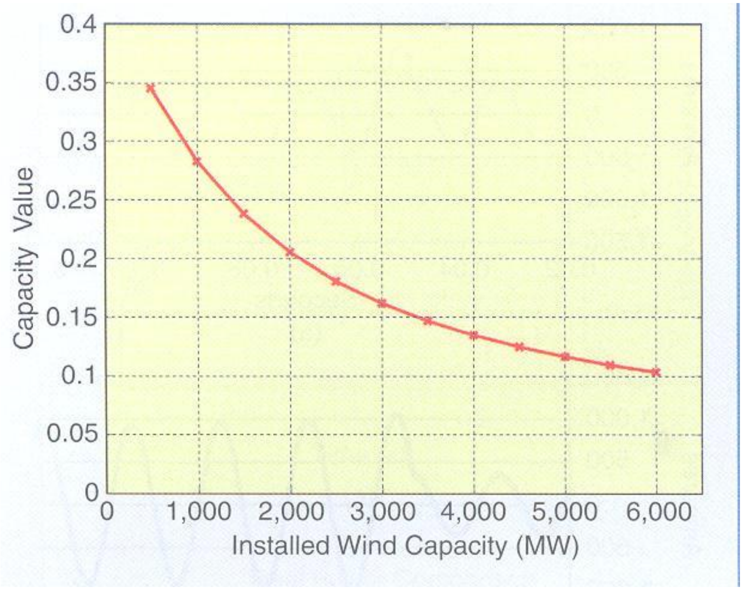

- ✓ The most significant factors are the correlation between the chronological curves of load demand and wind power generation as well as the time correlation of wind power generation across the power system.
- ✓ Capacity Credit has also a direct reward in the electric energy market.

Integration of Wind Generation

- ✓ Operational integration costs for wind:
  - cost of reserves to balance the variations of wind power generation (increase, decrease)
  - existing reserves for failures of generating units are deployed more often as wind power generation is added
  - additional thermal plants (with fast response) are needed as the wind penetration level increases (ancillary services).

- ✓ Regulating and load – following thermal plants for system ancillary services are forced to operate at reduced levels of efficiency resulting in increased fuel consumption and increased level of emissions.

Integration of Wind Generation

(continue)

- ✓ The existing thermal power plants are forced to operate at reduced levels of efficiency and for a smaller annual period affecting the financial viability of the relevant projects.
- ✓ The operational cost can potentially be reduced by using more advanced forecasting tools of wind power generation (when they become available).
- ✓ The costs of developing transmission networks to access wind resources are significant but they are smaller when compared with the costs of electricity production.
- ✓ New types of conventional generation technology could help in wind power integration.
- ✓ Interconnections with neighbouring systems can provide flexibility by enabling balancing among different areas.

Integration of Wind Generation

(continue)

✓ Wind power generation cannot be totally absorbed due to the following system technical causes and appropriate orders must be given to the relevant wind parks for generation reduction:

- I: Total amount of power output of the system generating units that are required to operate (technical limits of thermal plants, compulsory operation of RES installations).
- II: Additional amount of power output of system regulation units according to Reliability Criterion 4.
- III: Application of Criteria for the spinning reserve requirements of the system.
- IV: Application of an upper percentage level concerning the variations of wind power generation in consecutive hours.
- V: Application of an upper level concerning the system wind penetration (it can be applied only for security reasons).

Integration of Wind Generation

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✓ Regulatory decisions concerning the development of future combined cycle power plants and their impact on wind power integration:

- optimal number of shut down events for obtaining high reliability performance and acceptable maintenance costs
- operational schedule based on weekly or daily shut down events
- use of two or more gas turbines in weekly operational schedule for obtaining higher operational flexibility but with higher development costs
- use of one gas turbine in daily operational schedule with lower operational flexibility and lower development costs
- studies for determining the relative advantages and disadvantages.

Integration of Wind Generation

(continue)

- ✓ Application of appropriate measures for obtaining a more effective chronological load demand curve including demand management and charging facilities of electric vehicles.
- ✓ Application of hydrogen technology.
- ✓ The critical question exists for determining the limit of wind power penetration in order to ensure the acceptable level of system reliability and security.

Integration of Wind Generation

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✓ Power Storage Plants will be required:

- use of very flexible resources (such as hydroelectric reservoirs)
- equivalent wind penetration levels will increase
- economic value to the system exists even with no wind power generation but it will increase with its integration
- studies are needed to quantify the positive impact in relation with the existing technologies and the capital investment costs of the facilities
- decisions concerning their operational schedule in conjunction with wind power generation not being absorbed.

✓ System Operators will have additional work to perform and dedicated Control Centres may be required.

Power Generation from Photovoltaic Plants

✓ The amount of solar power generation connected to transmission and distribution networks is increasing significantly.

✓ The plant sizes increase resulting in higher penetration levels so that interconnection and operational challenges become more complex.

✓ The electrical behaviour of Photovoltaic (PV) systems is dominated by the inverter characteristics.

✓ It is necessary to model both real and reactive power from PV systems.

✓ In high penetration PV scenarios, transient PV output fluctuations may occur due to cloud transients and all possible impacts on system operation must be examined.

✓ PV impact studies concern both the transmission and distribution networks according to the connection point of the PV system and can be either steady-state or dynamic in nature.

Power Generation from Photovoltaic Plants

(continue)

- ✓ The operational impact can be studied by modelling the stochastic variability of solar generation and calculating appropriate indices quantifying its load-carrying capability and effects on the reserve requirements.
- ✓ The rising and setting of the sun regularly leads to 10%-13% changes in PV output over a period of 15 minutes (single-axis tracking PV plants).
- ✓ Clouds can change rapidly the power output of large PV plants and this fact causes significant concerns to system operators and planners.
- ✓ Clouds cause diverse changes in PV power output across plants and appropriate electrical connections can aggregate the diverse output of separate PV panels within a plant.

Power Generation from Photovoltaic Plants

(continue)

- ✓ In large PV plants (Grid plants), the output of an irradiance meter will show more severe ramps in times up to 10 minutes compared with the ramps of plant power output (10%-40%).
- ✓ Changes in PV power output can occur due to the simultaneous inverter trips within the plant following large grid disturbances. The application of Low-Voltage Ride-Through (LVRT) techniques will be needed for PV inverter design.
- ✓ Equipment outages in PV plants can occur and must be taken into account in the same way as the other system power plants.
- ✓ Future PV plant designs will permit their participation in power system operation (ancillary services) more effectively.

Computational Methodology for the Reliability and Operational Assessment of Power Systems

- ✓ Characteristics of Thermal Power Plants
- ✓ Characteristics of Large Hydroelectric Power Plants (HPP)
- ✓ Characteristics of Pumping Facilities in HPP
- ✓ Power Generation of Wind Parks and Photovoltaic Systems
- ✓ Criteria and Characteristics of Power System Operation
- ✓ Simulation of Power System Operation
- ✓ Calculation of Indices

Characteristics of Thermal Power Plants

✓ Steam turbines using various solid fuels

- Low production cost.
- Supply of system base load demand.
- Very small number of shutdown events.
- Minimum power output: 50% of maximum.

✓ Steam turbines using natural gas or diesel fuel

- Increased production cost.
- Limited number of shutdown events – limited time period of operation.
- Minimum power output: 35% of maximum.

Characteristics of Thermal Power Plants

(continue)

✓Combined Cycle Power Plants using natural gas

- Rapid change of power output.
- One steam turbine (ST) and one or more gas turbines (GT).
- Shutdown events: limited number – impact on maintenance and availability.
- Cogeneration Power Plants (continuous operation, two or more gas turbines, supply of thermal load demand).
- Minimum power output: - 60% of maximum when 1 GT exists

  - 35% of maximum when two or more GT exist

Characteristics of Thermal Power Plants

(continue)

✓Gas turbines and internal combustion engines using natural gas or diesel fuel

- Flexible generating units.
- Very high production cost.
- Operation during the system peak load demand periods and during the system risk states.
- Stuck probability of occurrence for start-up events.
- Minimum power output: 10% of maximum.

Characteristics of Large Hydroelectric Power Plants (HPP)

- Reservoirs with certain characteristics of water storage and operation.
- Hydrologic chains – Reservoirs located on the same water flow (i.e. river).
- Limited operation according to the available water quantities – Water management policies.
- Weekly modelling of water inflows into the reservoirs – Uncertainty of rainfalls at the respective area.
- Supply for social services (i.e. irrigation, water supply).
- Operation to avoid water overflows in the reservoirs and prediction of time periods with very high water inflows (November - March).
- Various types of hydrological years (dry, normal, wet).

Characteristics of Pumping Facilities in HPP

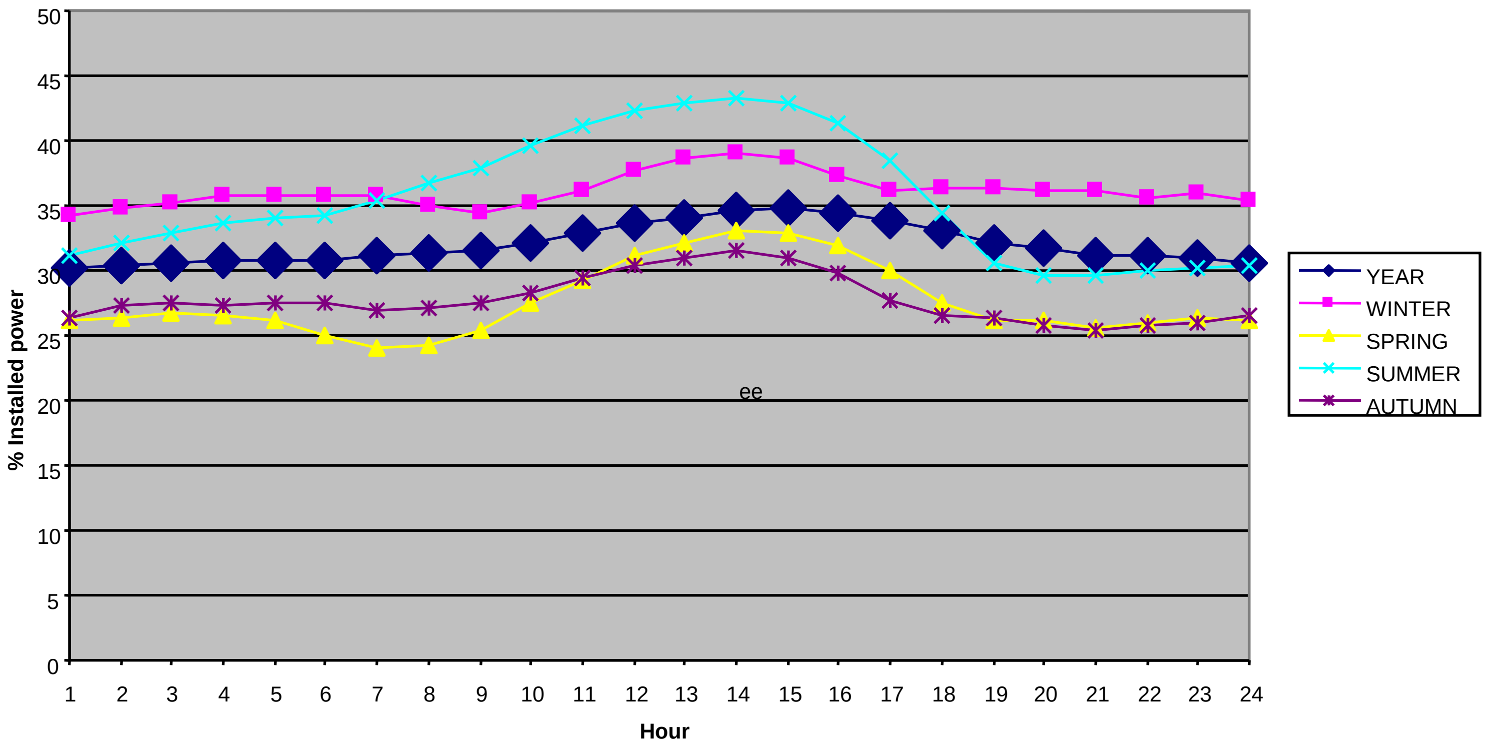
- In existing old pumping facilities, daily pumping operation (additional load demand) during the first hours of the day (01.00 – 07.00) and operation of the HPP during certain time periods of the day (11.00 – 13.00 and 18.00 – 22.00) in order to consume the pumped amount of water.
- Special operational features of the HPP pumping facilities can be handled.
- Future development of modern technology Pump Storage Plants with an operating policy that will permit the increased penetration of RES by absorbing the additional wind power generation.

Simulation of Power Generation from Wind Parks and Photovoltaic Systems

- Equivalent daily curves are calculated for each month of the year from the statistical analysis of available data concerning the power generation of the wind parks (mean value and standard deviation of the average hourly wind power generation).
- Equivalent daily curves for each month of the year are calculated that quantify the average increase and/or decrease of the average hourly wind power generation of the entire system in two consecutive hours.
- The variables of the above curves are stochastic variables that follow certain probability distributions.
- These curves are used for predicting the wind power generation of the entire system during the simulation procedure.
- Similar curves and a computational procedure are applied for predicting the available total power generation of the photovoltaic systems by using their respective available data.

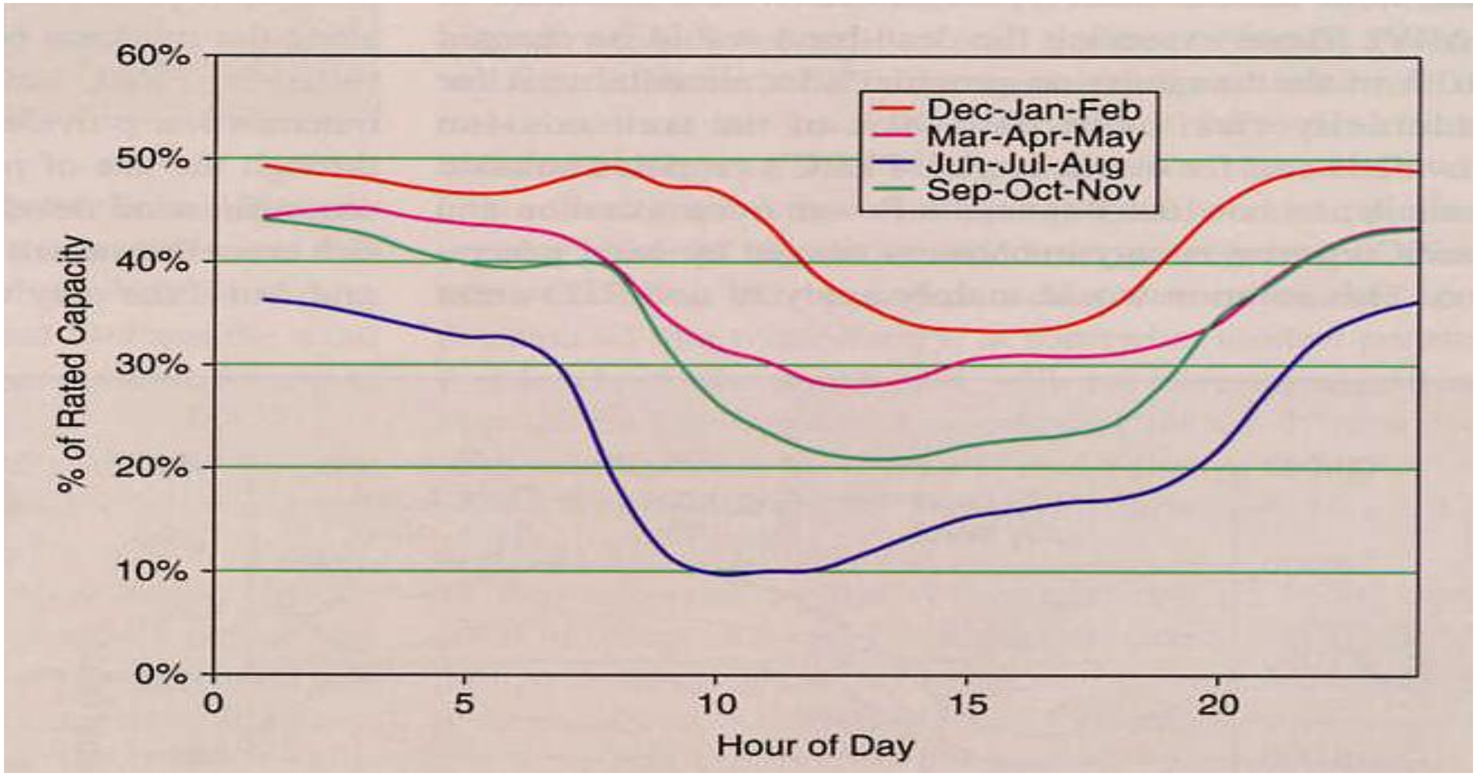
Hourly Wind Power Generation of an Equivalent Day (% of installed capacity)

Wind Scenario 3000 MW in Greece (Entire year and each season separately)



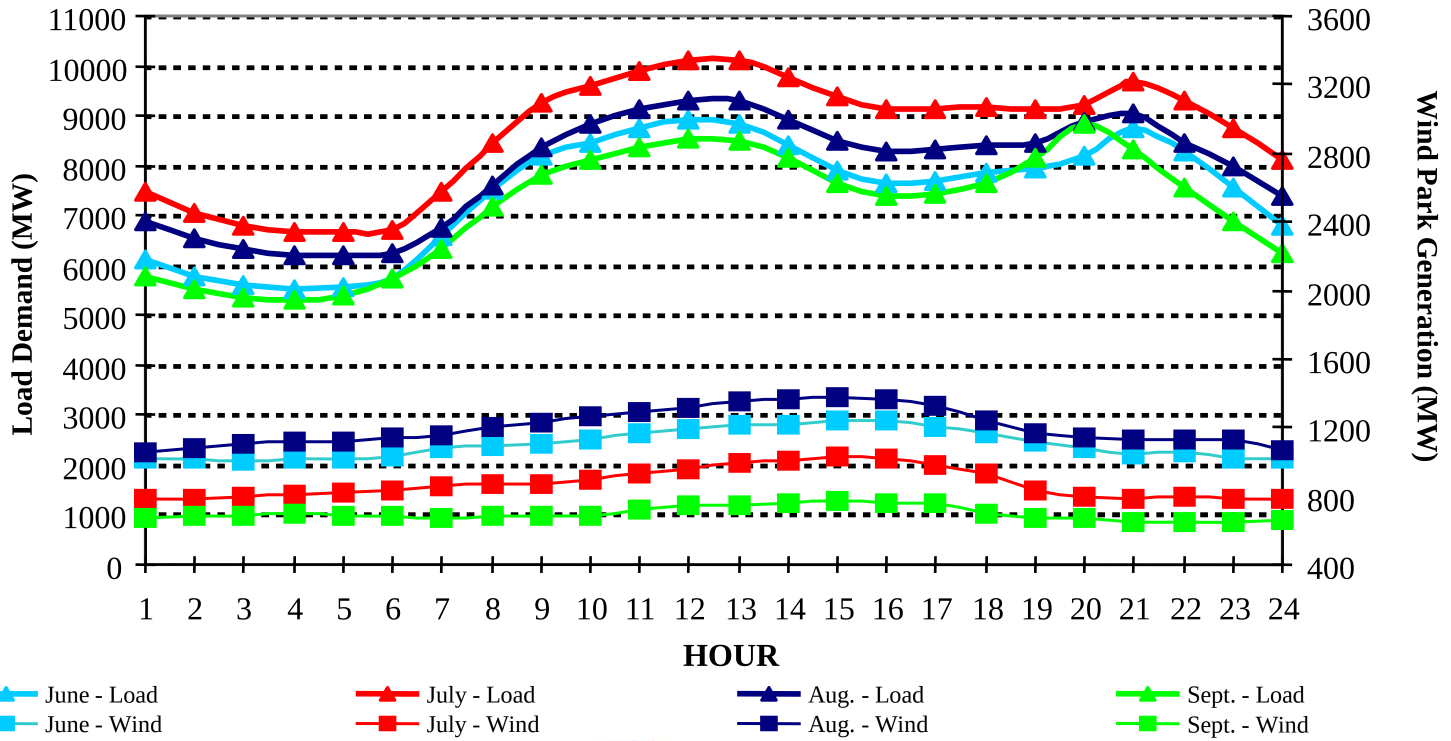
Hourly Wind Power Generation of an Equivalent Day (% of installed capacity)

(USA Electric Power System – each season separately)



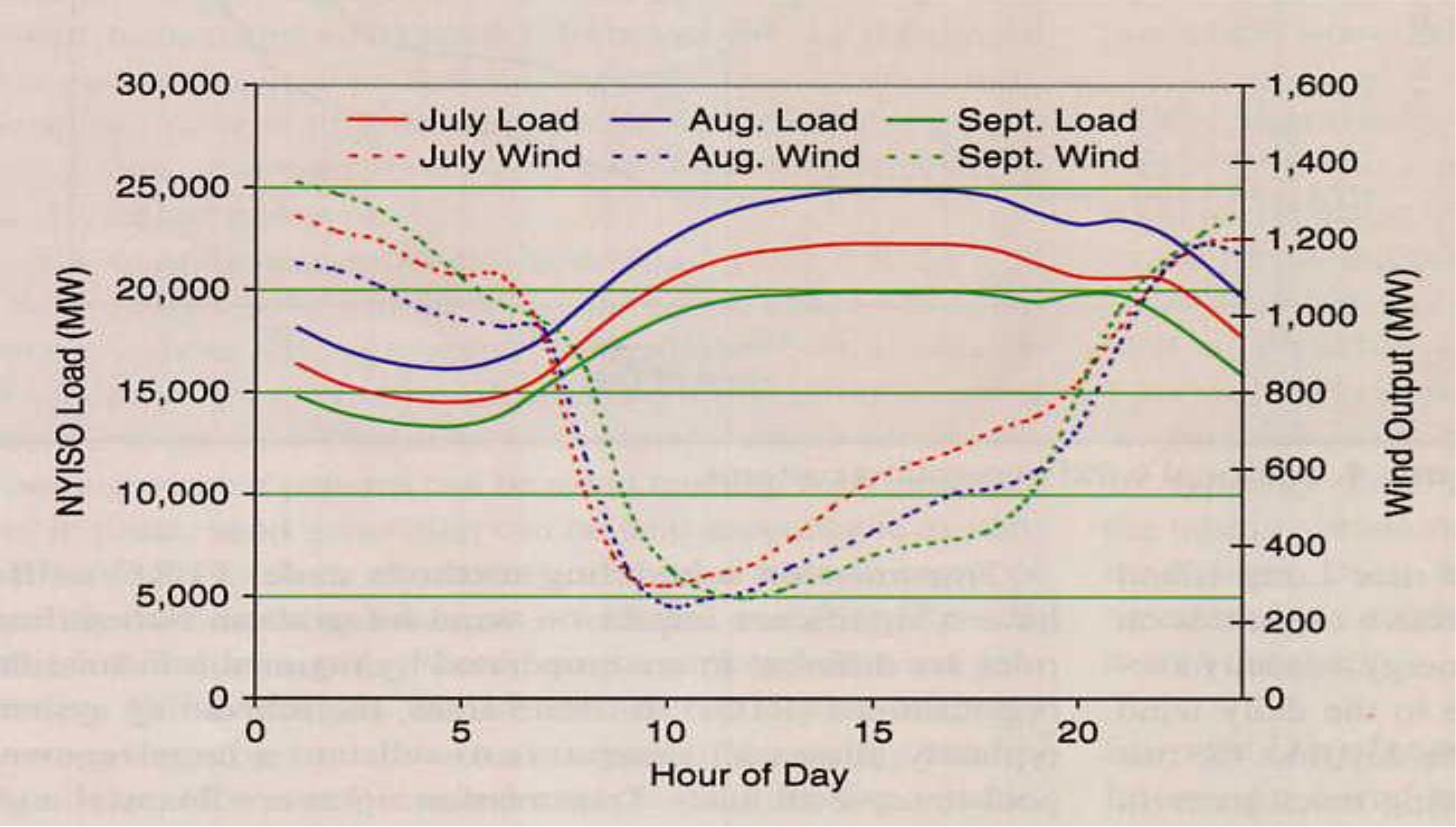
Correlation of Average Hourly Wind Power Generation with Average Hourly System Load Demand

Wind Scenario 3000 MW in Greece (July - September)



Correlation of Average Hourly Wind Power Generation with Average Hourly System Load Demand

(USA Electric Power System)



Criteria and Characteristics of Power System Operation

- ✓ The level of spinning reserve capacity is determined by combining appropriately the relative values of the following three criteria:
  - **Reliability Criterion 1**: Largest power output of the generating units in operation (N - 1).
  - **Reliability Criterion 2**: It is a constant value.
  - **Reliability Criterion 3**: It concerns the sudden reductions of wind power generation and has a constant value or a certain percentage of wind power generation.
- ✓ **Reliability Criterion 4** (Reverse Spinning Reserve) : Power output capacity in certain generating units (Regulation) to be reduced within a very short time period. It is used during events of sudden increases of wind power generation and it is determined by either a certain percentage or a constant value.

Criteria and Characteristics of Power System Operation

(continue)

- ✓ An upper output level is applied for each generating unit of the electric power system in order to satisfy the requirements of system primary frequency regulation.
- ✓ Regulation Units: Certain combined cycle power plants with equal allocation of the required regulation load.

Simulation of Power System Operation

- Two alternative unit commitment procedures (algorithms) are applied, by considering the operational requirements of the combined cycle power plants (annual number of shutdown events less than 50), for the following simulation time periods:
  - Weekdays Time Period (08.00 Monday – 22.00 Friday): No shutdown events may occur for the Combined Cycle Power Plants unless there are certain technical problems of the system.
  - Weekend Time Period (22.00 Friday – 08.00 Monday): Shutdown events may occur for the Combined Cycle Power Plants.

Simulation of Power System Operation

(continue)

- Appropriate unit commitment algorithm for each simulation hour.
- The total wind power generation is absorbed by the system unless there are certain technical problems.
- Appropriate annual chronological curves are used for calculating the hourly wind power generation for each wind park.

Simulation of Power System Operation

(continue)

- Calculation of the power being produced by the available system generating units being in operation and the wind power generation being absorbed by the system so that:

  System Total Power Generation = System Load Demand (a)

- Calculation of the available level of spinning reserve capacity by certain generating units:

  Spinning Reserve Capacity $\geq$ Capacity calculated by applying Reliability Criteria 1, 2 and 3 (b)

- It is considered that the system resides in:
  - Healthy State: if both (a) and (b) are satisfied.
  - Marginal State: if (a) is satisfied and (b) is not satisfied.
  - Risk State: if neither (a) nor (b) is satisfied.

Calculation of Indices

- ✓ Reliability indices (Loss of Load Expectation, Loss of Energy Expectation, Expected Frequency of Load Loss).
- ✓ Energy balance indices for each type of conventional generating plants and RES technologies.
- ✓ Equivalent CO_2 emissions for each conventional generating plant separately and the total generation system by considering all types of emissions (CO_2, NO_x, SO_x, Pm_{10}).
- ✓ Operational performance indices for conventional generating plants.
- ✓ Reduction events of wind power generation (overall and for each cause separately).

Analysis of a Practical System: Hellenic Electric Power System

- Year of Analysis: 2015.
- Load Demand
  - Standard Scenario: Peak 11440 MW, Energy 60212 GWh.
  - Energy Saving Scenario: Peak 11080 MW, Energy 58425 GWh.
- Maximum Power Generation (except wind parks): 13200 MW.
- 23 Thermal Power Plants (1 Cogeneration Plant)
  - 61 Generating Units
  - Maximum Power Output: 10922 MW

Analysis of a Practical System: Hellenic Electric Power System

(continue)

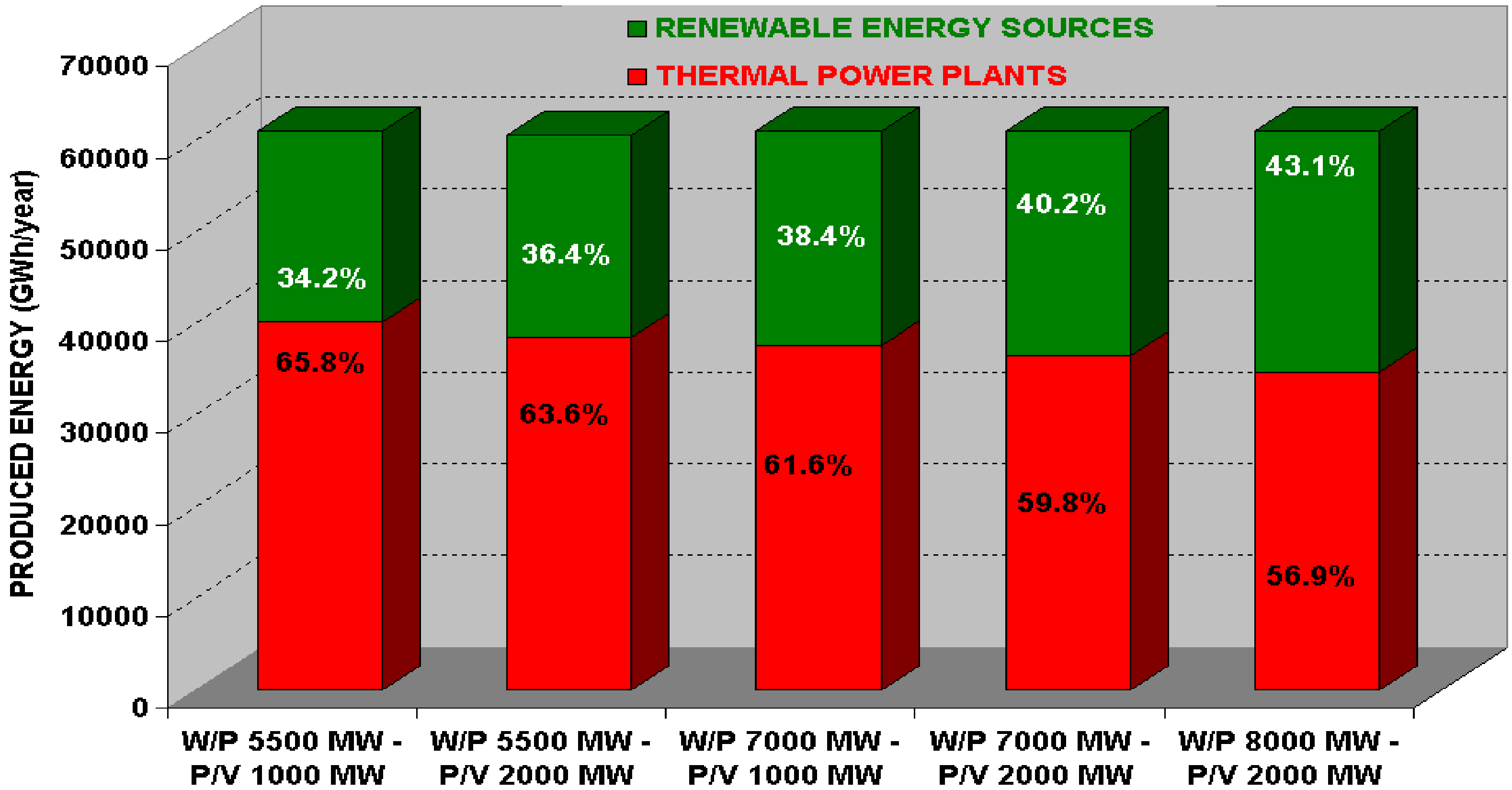
- 20 Large Hydroelectric Power Plants (HPP)
  - 53 Generating Units
  - Maximum Power Output: 3390 MW
- Different Penetration levels of power generation from Wind Parks and Photovoltaic Systems.
- Maximum Power Generation from other technologies of RES plants (SHPP, CP, BI): 450 MW.

Assessment Studies for the Operational Performance of the Hellenic Power System

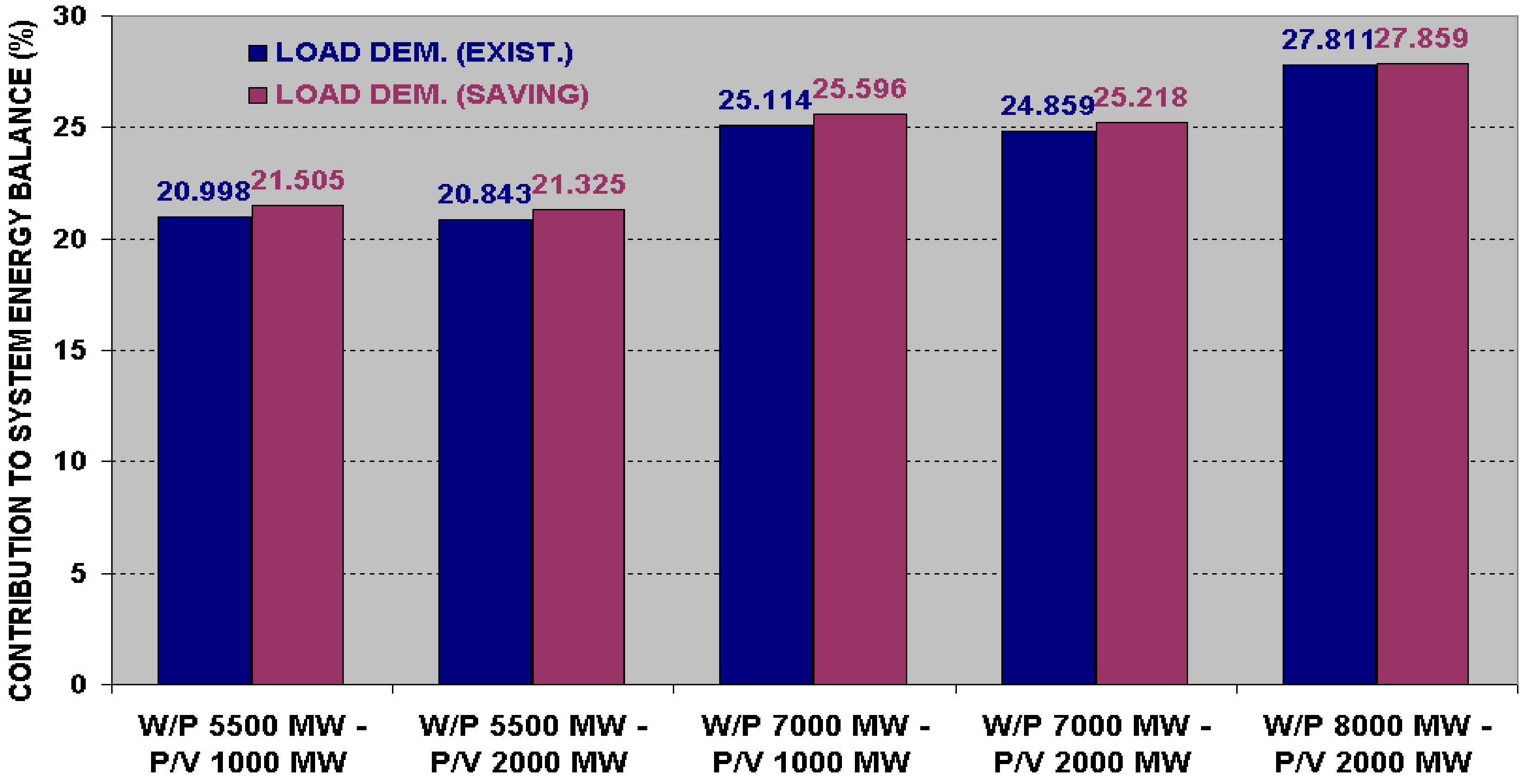
Alternative case studies that concern:

- Load Demand.
- Generation Mix.
- Market Rules.
- Safety and Reliability Criteria.
- Operational Rules and Practices.
- Technical Parameters and Specific Characteristics of Generating Units.
- Meteorological Data being used for assessing the expected contribution of RES generating units.
- RES penetration scenaria: Installed capacity for wind parks varies between 5500 MW and 8000 MW and for photovoltaic systems is either 1000 MW or 2000 MW.

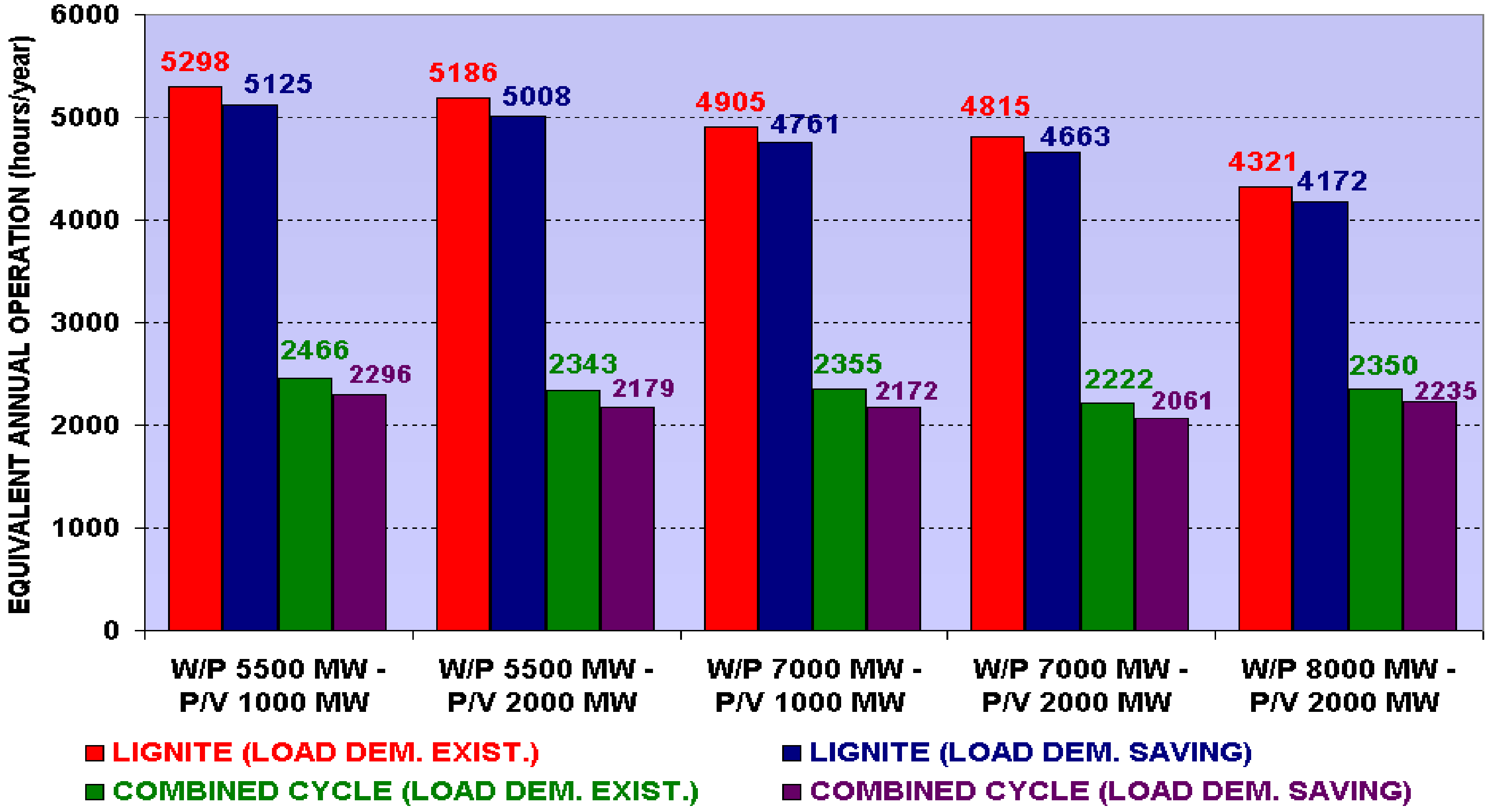
Contribution of Thermal Power Plants and RES Facilities to the System Energy Balance



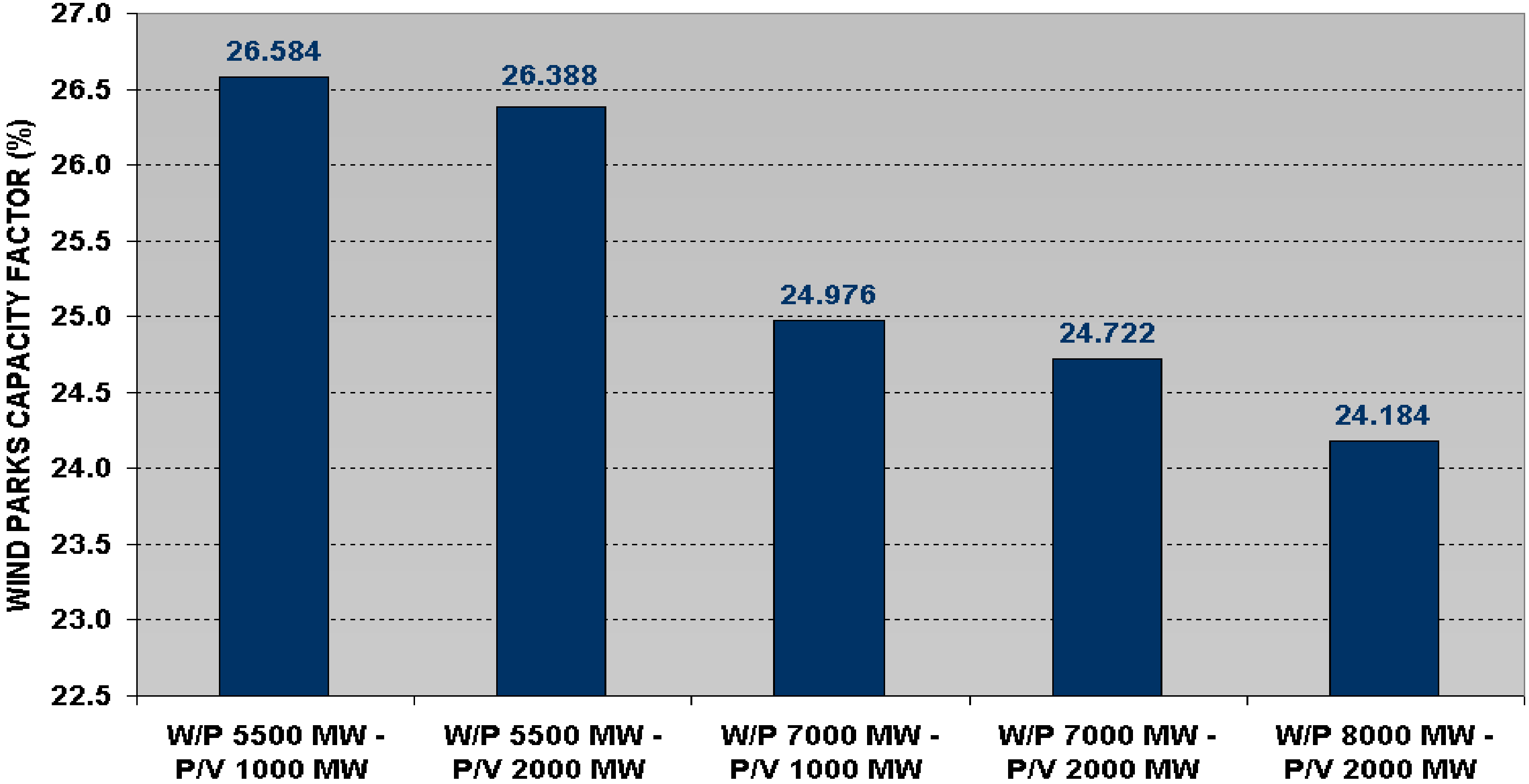
Contribution of Wind Parks to the System Energy Balance



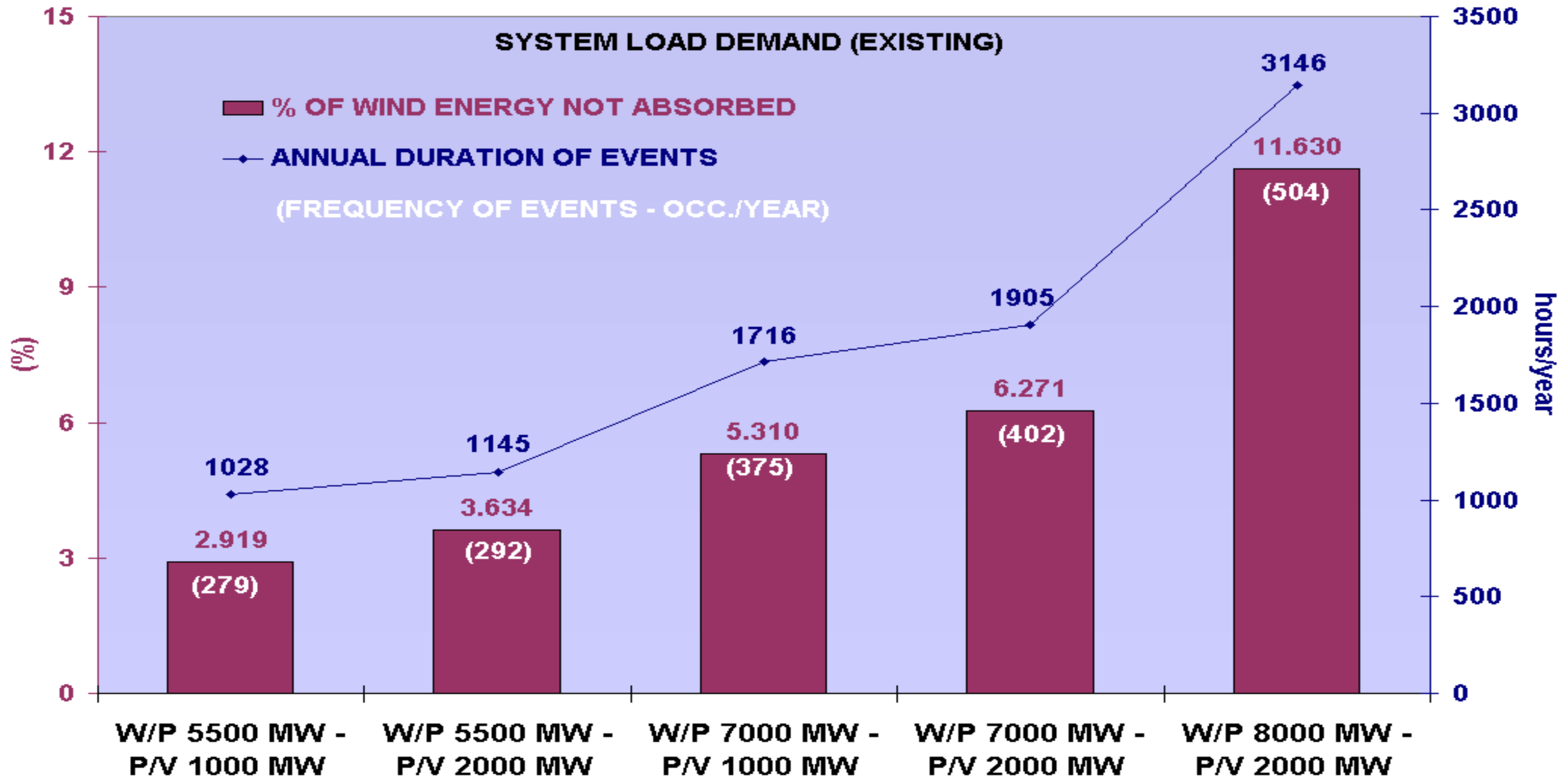
Equivalent Annual Operation of Thermal Power Plants



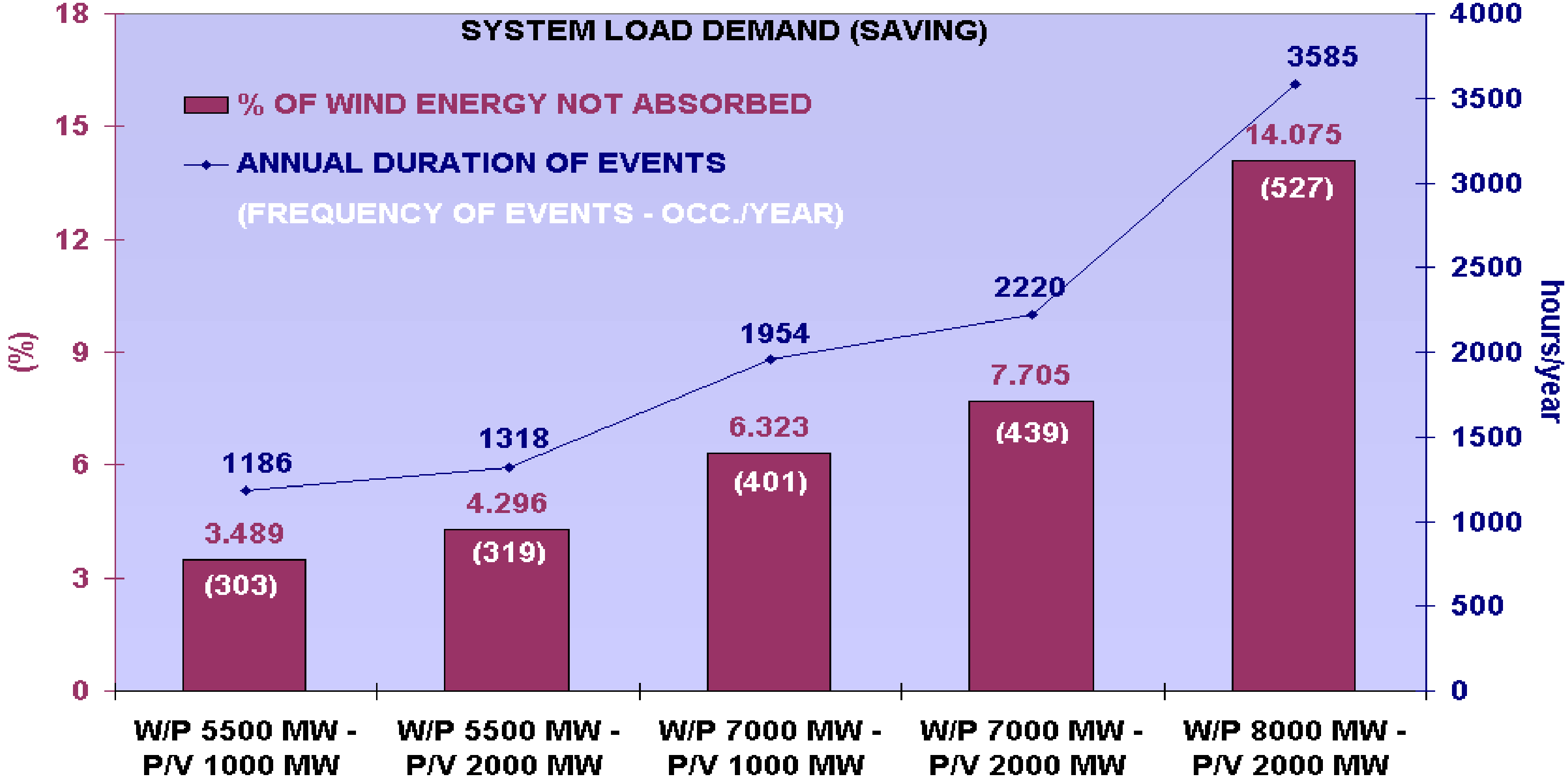
Capacity Factor of System Wind Parks



Reduction Events of Wind Power Generation (Standard Load Demand Scenario)



Reduction Events of Wind Power Generation (Energy Saving Scenario)



Conclusions

✓ The integration of high wind penetration can be handled effectively by taking into account the:

- continued improvements in generation technologies for thermal plants
- emergence of demand response
- smart grids
- advanced tools for wind power forecasting
- enlargement of balancing areas
- use of appropriate storage facilities
- participation in ancillary services
- use of dedicated Control Centres for RES installations.

Conclusions

(continue)

- ✓ The increasing penetration levels of RES installations will change considerably all aspects concerning the operational and reliability performance of future power systems.
- ✓ A low emission energy performance can be obtained by increasing the penetration levels of wind parks and photovoltaic systems (maximum decrease is equal to approximately 20%).
- ✓ The capacity factor of the system wind parks will decrease as the wind penetration level increases (maximum decrease equal to approximately 9%).

Conclusions *(continue)*

- ✓ The contribution of the wind power generation to the energy balance of the system is significant (20.8% - 27.9%) while it is expected to increase when energy saving measures will be applied.
- ✓ The contribution of all the renewable energy sources to the energy balance of the system is significant (34.2% - 43.1%) while the national targets are feasible when the features of the respective case studies will be achieved.
- ✓ The installation of a large number of wind parks may prove to be less efficient than it is expected when the required system design and operational parameters are not taken into consideration properly.
- ✓ The wind power generation that is not absorbed may be significant (2.9% - 14.1% of the total annual energy being produced) and reduction events will occur.

Conclusions *(continue)*

- ✓ The frequency of occurrence and the duration of the reduction events need to be considered thoroughly since they are expected to increase significantly as the wind penetration level increases and indicate the required operational actions that need to be performed by the System Operator.
- ✓ It is expected that the obtained results will increase with the installation of additional capacity of wind parks and photovoltaic systems.
- ✓ A significant reduction occurs for the equivalent annual operation of thermal power plants when the penetration level of RES installations increases and financial problems may be caused to the development of the respective projects.