Integration of variable renewable technologies (VRE) into power systems

Review of impacts and solutions for non-engineers

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The World Bank

FAQs

- **What are the impacts of variable renewables (VRE) on grid operations and planning ?**

- **What are the impacts of transmission on VRE?**

- **Can the grid be reliably operated at high levels of VRE? Do VRE need back-up generation?**

- **To what extent renewables contribute to the supply adequacy, and at what costs ?**

- **Can we install VRE in any system, in any node?**
- **How much VRE is it possible to integrate in a power system?**

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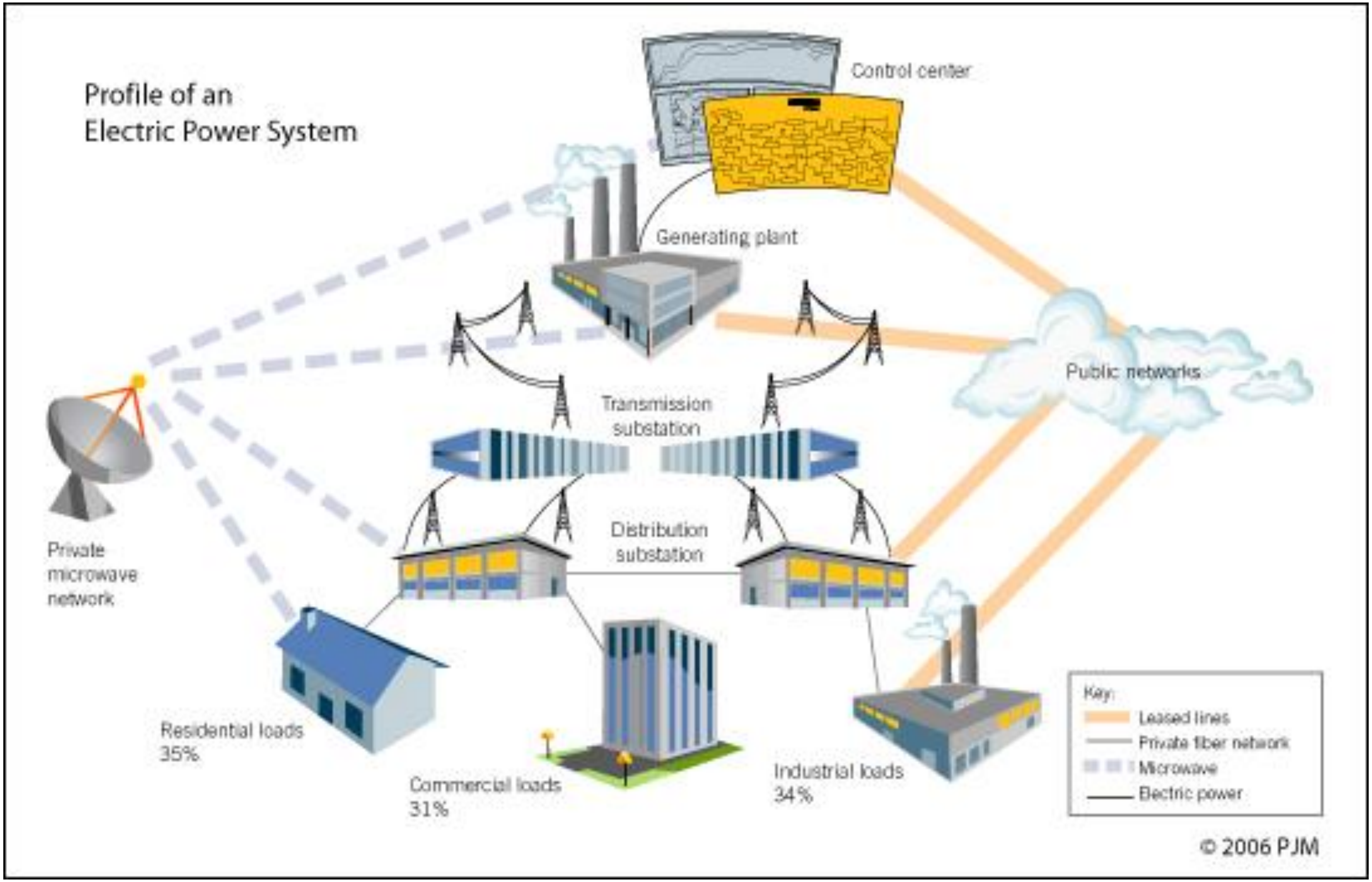
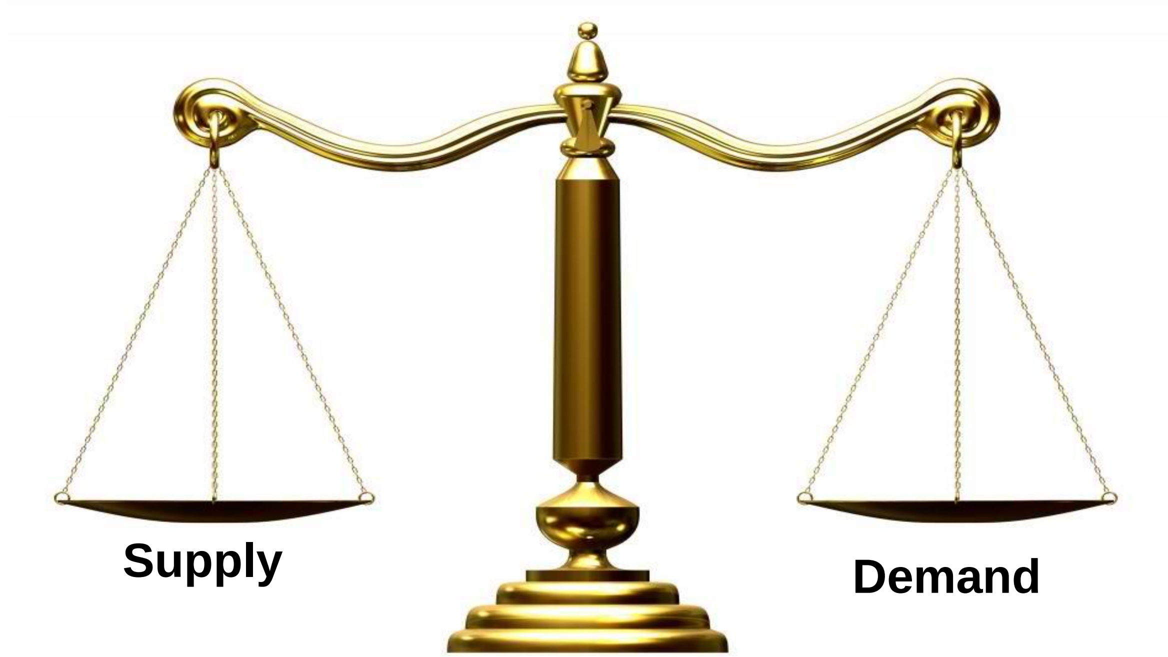
Power system basics



Power system basics

Operator responsibility

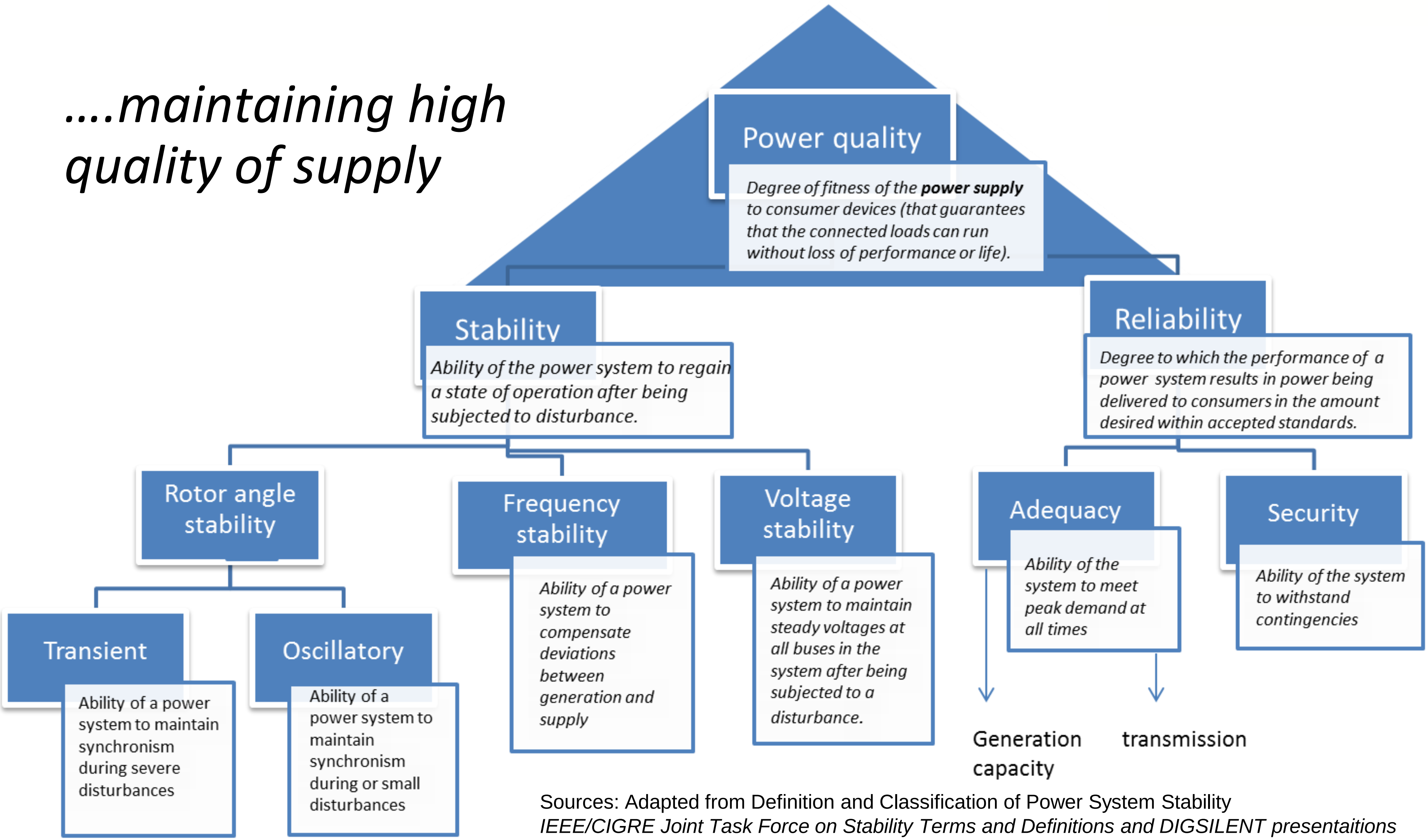


*Maintaining the **Balance** between Supply and Demand …*

Source: Adapted from Lawrence Jones presentation at the WBG

Power system basics

….maintaining high quality of supply



Sources: Adapted from Definition and Classification of Power System Stability *IEEE/CIGRE Joint Task Force on Stability Terms and Definitions and DIGSILENT presentaitions*

Power system basics

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All the functions should be integrated so that the system works to deliver electricity at all times: adequately, securely, with quality and desired cost and environmental characteristics

Transmission and distribution

- Expansion
- Access
- Tariff regulation
- Service quality

Generation markets

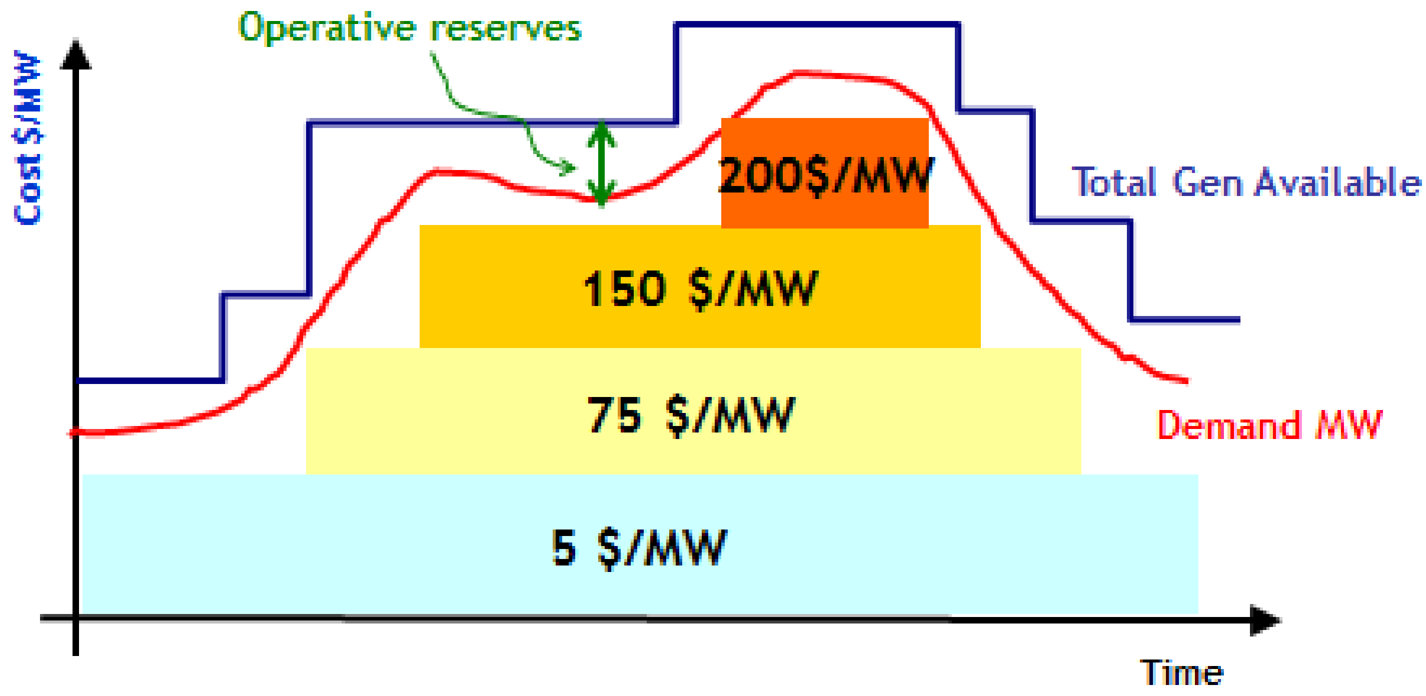
- Type and number of sport markets (*day ahead, intraday*)
- Bilateral contracts (*physical, financial*)
- Supply adequacy function: long-term signals for investment (*capacity payments, reliability auctions*)
- Demand Side Management (DSM) and Participation

Ancillary services

- Real time operations
- Reserves real and reactive
- Frequency control
- Voltage control

Source: Marcelino Madrigal presentation of Power systems

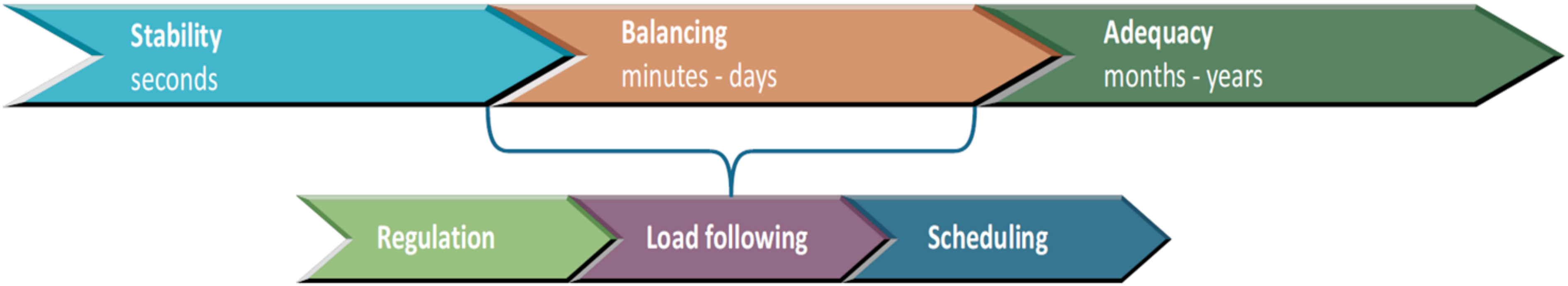
Power system basics



Simplified representation

Source: Marcelino Madrigal

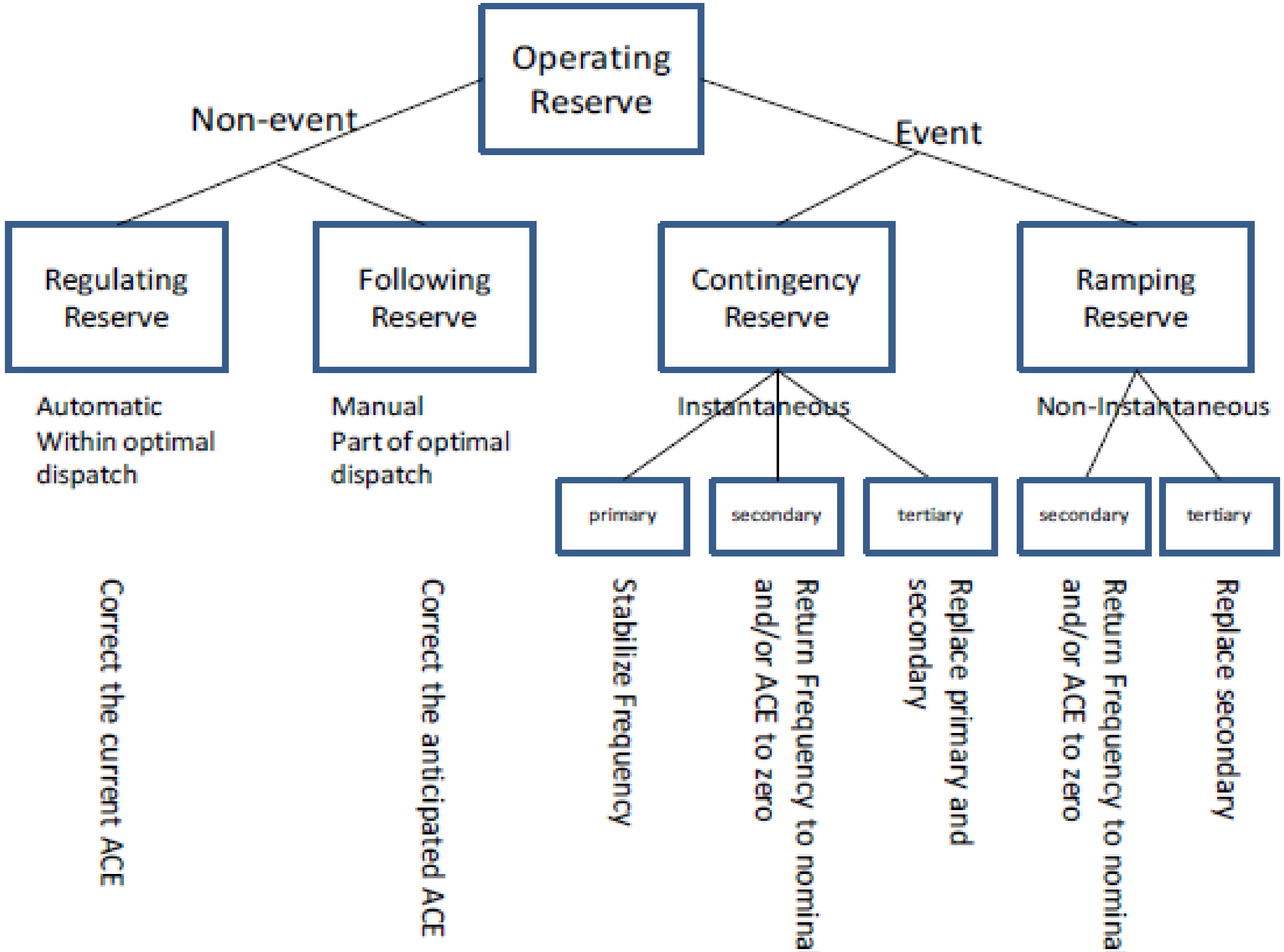
Power system basics



	Response time	Duration
Regulation	~ 1 minute	10 minutes
Load-following	~10 to 30 minute	1 hr
Scheduling	~ 1 day	6 hrs

International Energy Agency. *Harnessing Variable Renewables: A Guide to the Balancing Challenging*, 2011. www.iea.org/publications

Power system basics



*Source: **Operating Reserves and Variable Generation** *A comprehensive review of current strategies, studies, and fundamental research on the impact that increased penetration of variable renewable generation has on power system operating reserves..* Erik Ela, Michael Milligan, and Brendan Kirby . NREL aug. 2011

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Characteristics of VRE

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Location specific	• Implications on Transmission and distribution planning
Variability	• Load varies by seconds, minutes, hours, by day, weather • Variable generation vary based on fuel availability • Dispatchable generation may not be available
Uncertainty	• System operational decision is made by using the best available forecasts (load, generation, etc) • Forecast error is common – there is no perfect forecast • Dispatchable resources may deviate from scheduled set points

Source: Adapted from Lawrence Jones presentation at the WBG

Characteristics of VRE

Location specific: Why is transmission for VRE different?

- Resources are often "misplaced": far away from consumption or existing network
- Scaling-up requires exploiting hundreds of sites whose average size is "small" (~100 MW and lower)
- Frequently building transmission will take more time than building, e.g., the wind power plant
- Bankability may be conditioned to the existence of transmission
- Transmission cost can impact the LCOE and financial returns

Characteristics of VRE

Variability and uncertainty

It is not a new challenge…

Demand has been always variable

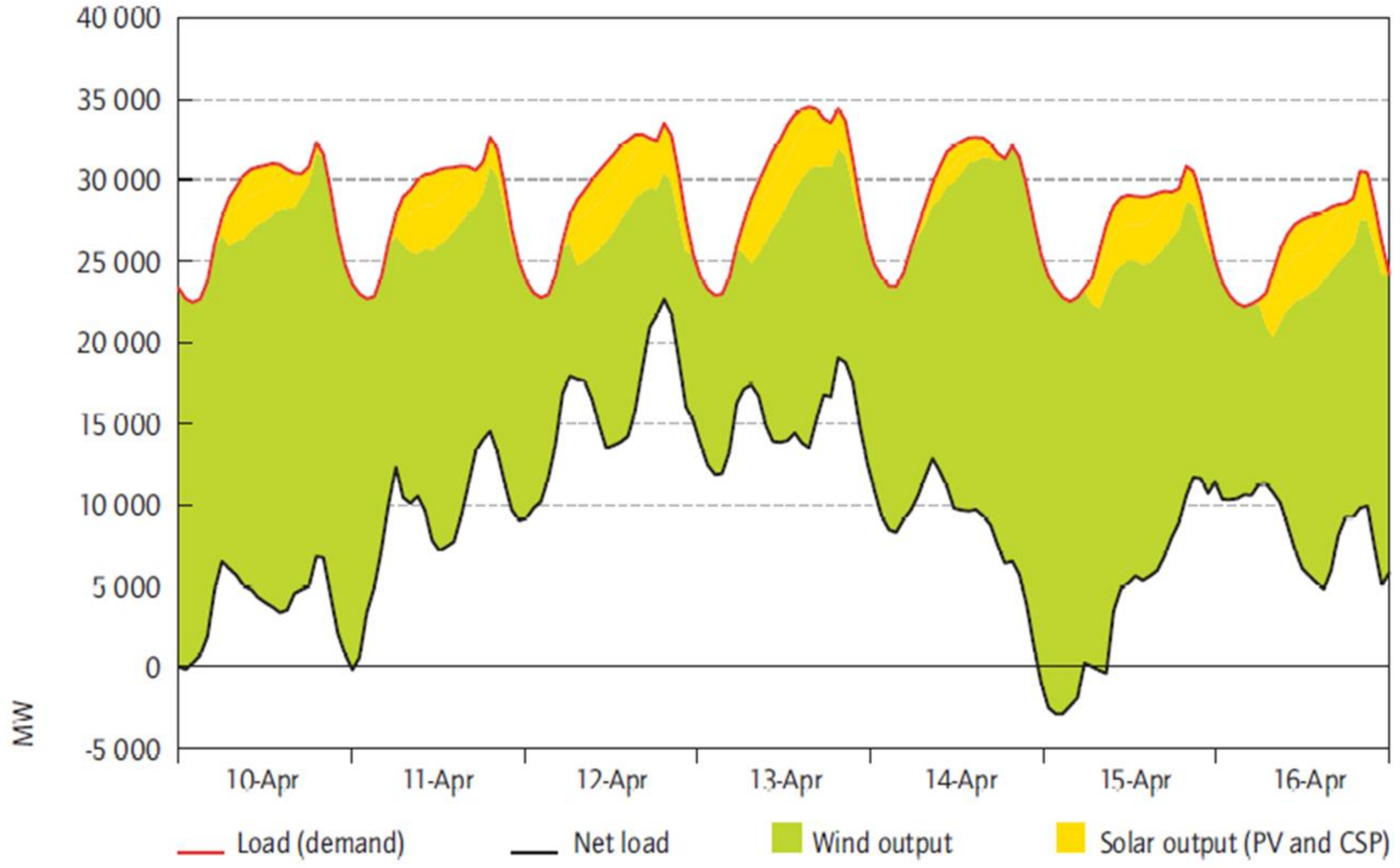
Now Supply is also variable

Source: Adapted from Marcelino Madrigal presentation for Mexican Authorities

Characteristics of VRE

Variability and uncertainty

How challenging it is? depends how the aggregated impacts combine load – supply: Net load



Source: IEA

Characteristics of VRE

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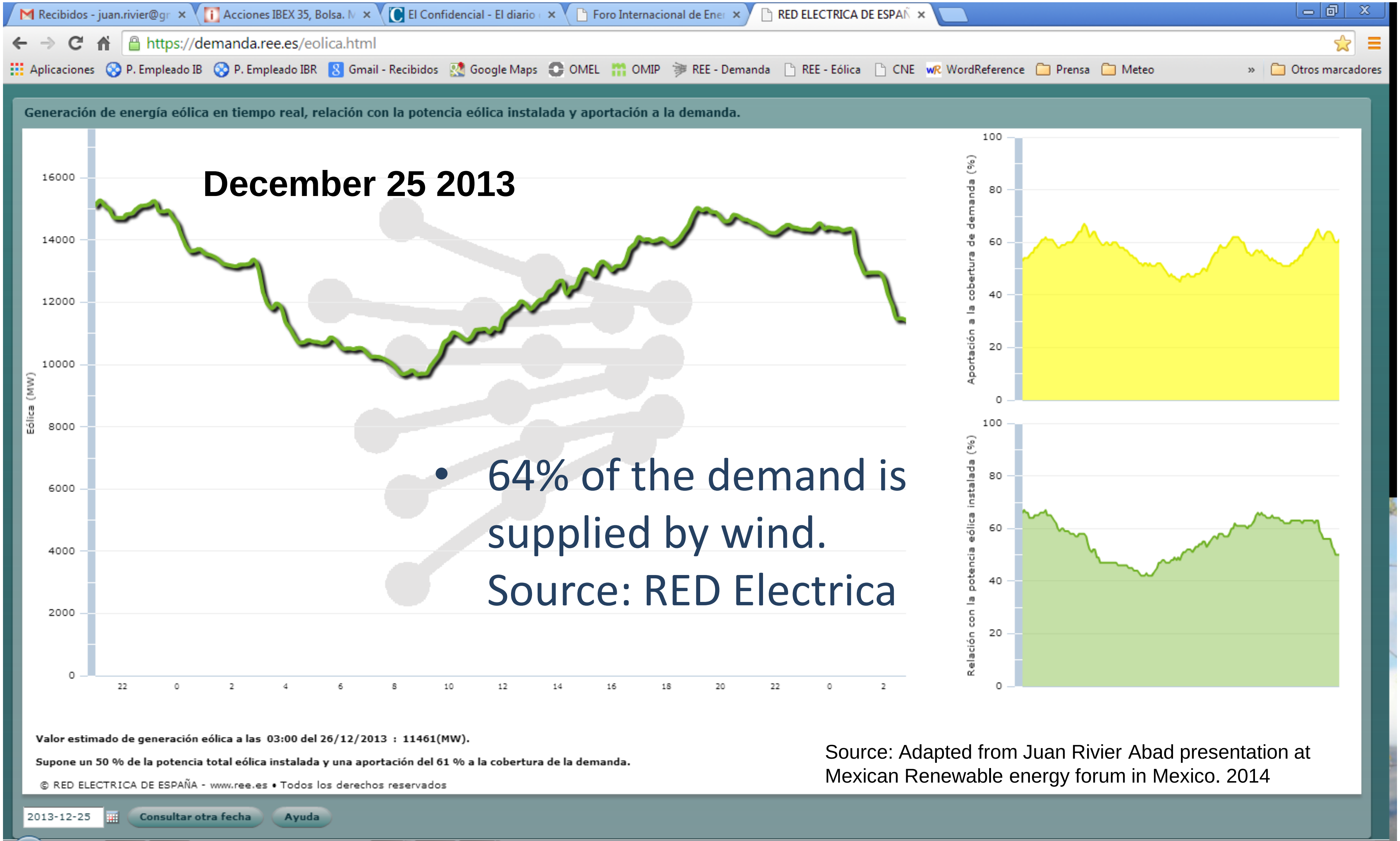
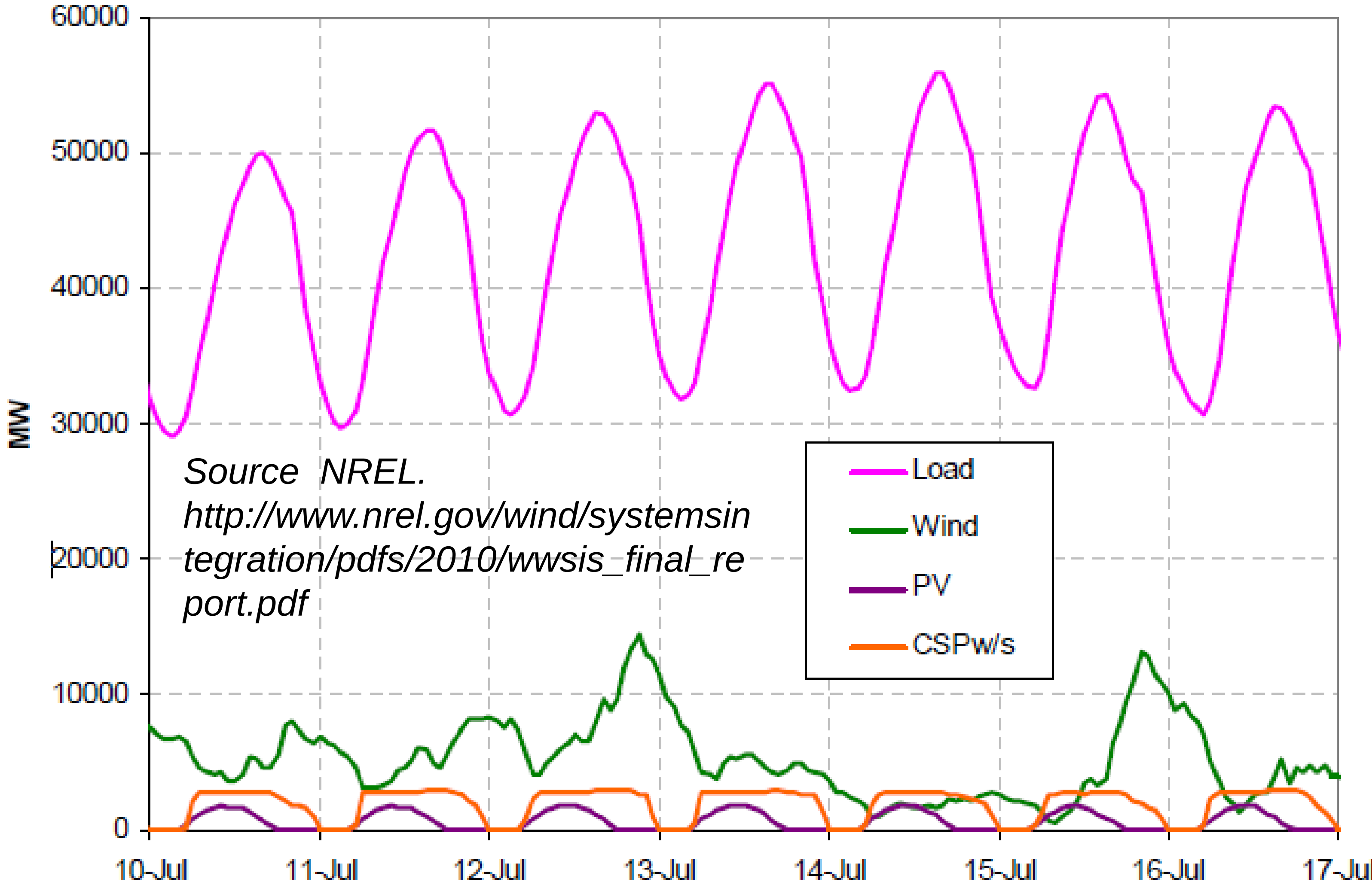


- 64% of the demand is supplied by wind. Source: RED Electrica

Source: Adapted from Juan Rivier Abad presentation at Mexican Renewable energy forum in Mexico. 2014

- Solar is more predictable, largely coincide with demand and counter cyclical to wind



Source NREL. http://www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_final_report.pdf

Contents

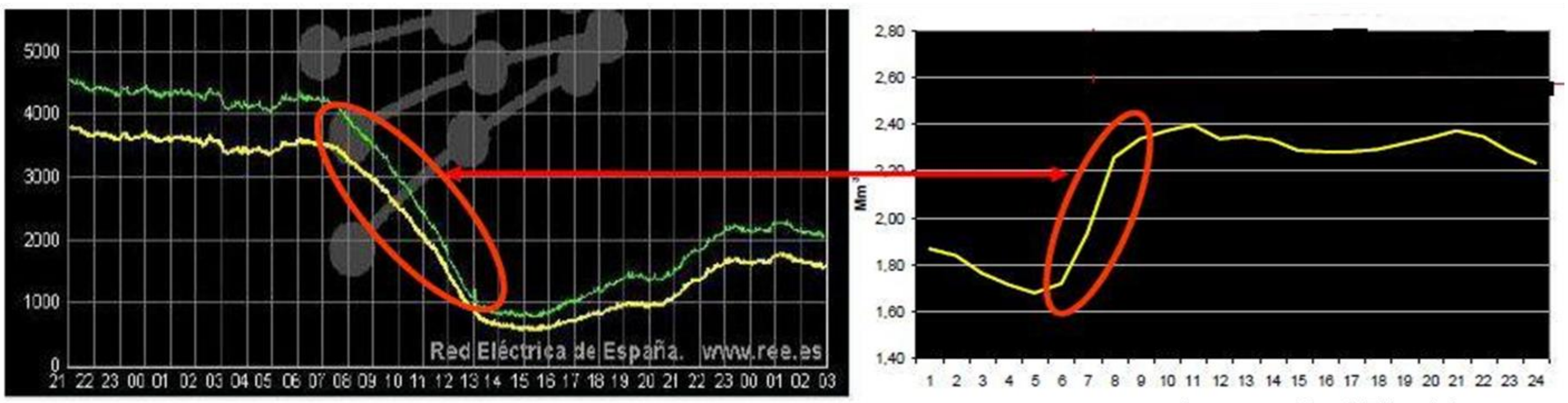
- Power system basics
- Characteristics of Renewables
- Impact on system operations
- Solutions for integration of VRE into power systems
- Conclusions

Impacts on system operations

- Operational impacts of WIND:
  - **Second to second (intra-minute)**
    - Wind power variations are insignificant, do not tend to impact big systems, need for regulation services.
  - **Minute to minute (intra-hour)**
    - A bit more variability than sec. to sec. requiring real time, or load-following services
  - **Hour to hour (intra-day)**
    - ***Tend to be more significant and affect intra-daily dispatch.*** Storm transitions take place in this time frame leading to cut-off speeds or zero speeds. Ramping.
  - **Day to day and beyond (seasonal)**
    - More predictable, affect long term energy availability (energy quality of the resource) and contribution of the resource to adequacy.

Impacts on system operations

Special conditions: Spain min load max wind: CCGT Flexibility



Source: Red Electrica

- Wind power output reduced by 75% in 6 hours, decrease met by fast responding CCGT

- Fast start units need be available to compensate for the loss: in this case CCGT

- Other options that can help: interconnections (as in Denmark), demand response, more wind and solar diversity. Which is the lower-cost option ? reserves/interconnections ?

Impacts on system operations

Special conditions: Ramp-rates and the importance of good forecasting

- Wind output can have fast and slow ramp rates
- These variations are not “intermittent” since they are not “contingency-like” or 0/1 events
- Slow ramps are easier to predict than fast ramps
- Slow ramps require better dispatch resolution and integrating forecasting into-dispatch
- Faster ramps can have impacts on frequency specially on small systems or when shares of RE are really high (>20% etc).

Impacts on system operations

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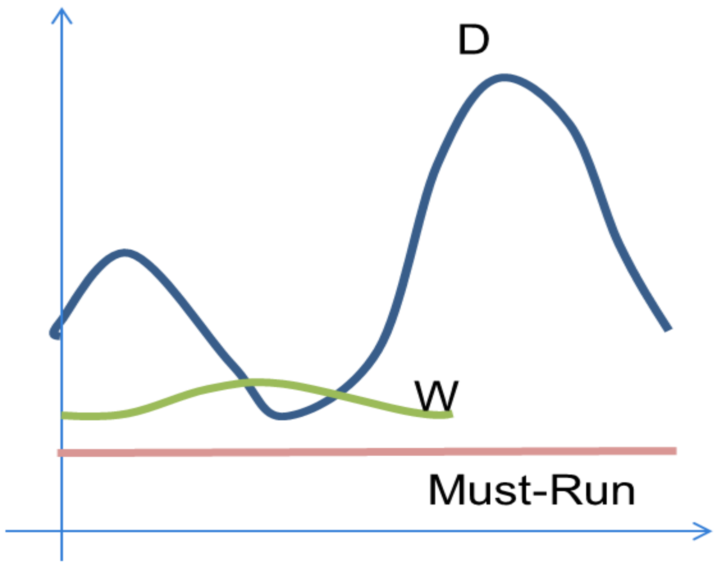
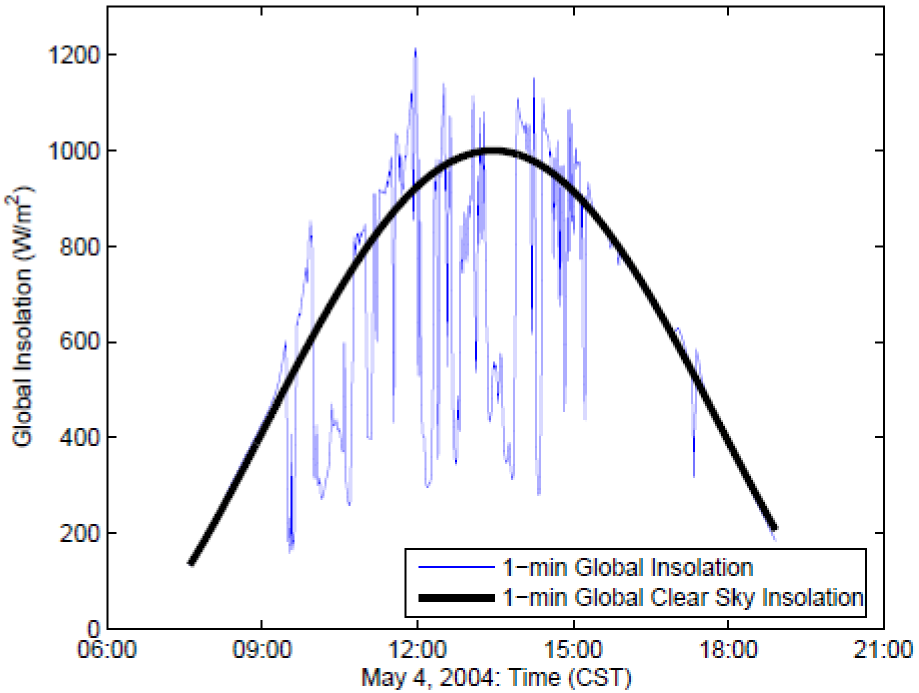
Special conditions: Maximum Wind Output During Low Demand

- This is becoming de firs de-facto a first technical "limit" to wind
- Wind output tends to be high during low-demand
- During low-demand some generation units must-run (technical limits, inertia, or minimum-take contracts
- Wind output surpasses minimum demand and needs be curtailed or other solutions need be found
  - Re-dispatch generation
  - Re-furbish or retire old power plants with minimum must-runs
  - Need to have flexible contracts
  - Build more transmission to share wind



Impacts on system operations

- Solar variability can become more acute during cloudy patches



(a) Example of 1-min global insolation and global clear sky insolation on a partly cloudy day

: Implications of Wide-
ı Geographic Diversity for
rt-Term Variability of Solar
er. Andrew Mills and Ryan
er Ernest Orlando Lawrence
‹eley National Laboratory

- High solar does not happens during low-load (an issue with Wind)

Impacts on system operations

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- Sand storms seem to have a very similar transitory (minutes) impact as cloudy patches

- Sand accumulation in PV can reduce output (20-30 %) until panels are not cleaned (hours/days)

- Masdar City 10 MW solar PV, episode in 2009: "…when the amount of suspended dust in the air was between 1,500 and 2,000 parts per million – more than 10 times higher than normal – the plant functioned at 60 per cent of its capacity, said Khaled Awad, director of Masdar City…"

Source: http://ecoperiodicals.com

Impacts on system operations

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- **"Integration" studies can be used to estimate some of these impacts**
  - There is not an standard procedure, but
  - Usually they involve dispatch-like simulation with very short-time step (a few minutes, up to an hour) and cover extended periods
  - Various weeks, different seasons, and sample years (5+, 10+ years) as aggregation of variables is assumed to increase
  - Analyze the cost of the system with and without variables
  - Very data intensive, sound data of expected high resolution (few minutes) variability is key in this studies
  - The "science" is still evolving, but some findings or trends are very informative

Impacts on system operations

- Observable trends

  Wind short-term integration costs are non-zero:

  For levels below 10% of energy integration costs are small

  1-5 $/MWh

  For levels 10% to 15% more impact on operative reserves, and other services. Detailed studies recommended

  3-5 $/MWh

  For levels 15% to 30% more flexibility will be required, large interconnected areas, technology and location diversity. Studies highly recommended

  5-10 $/MWh

•Each system "flexibility" will drive if impacts appear sooner or later

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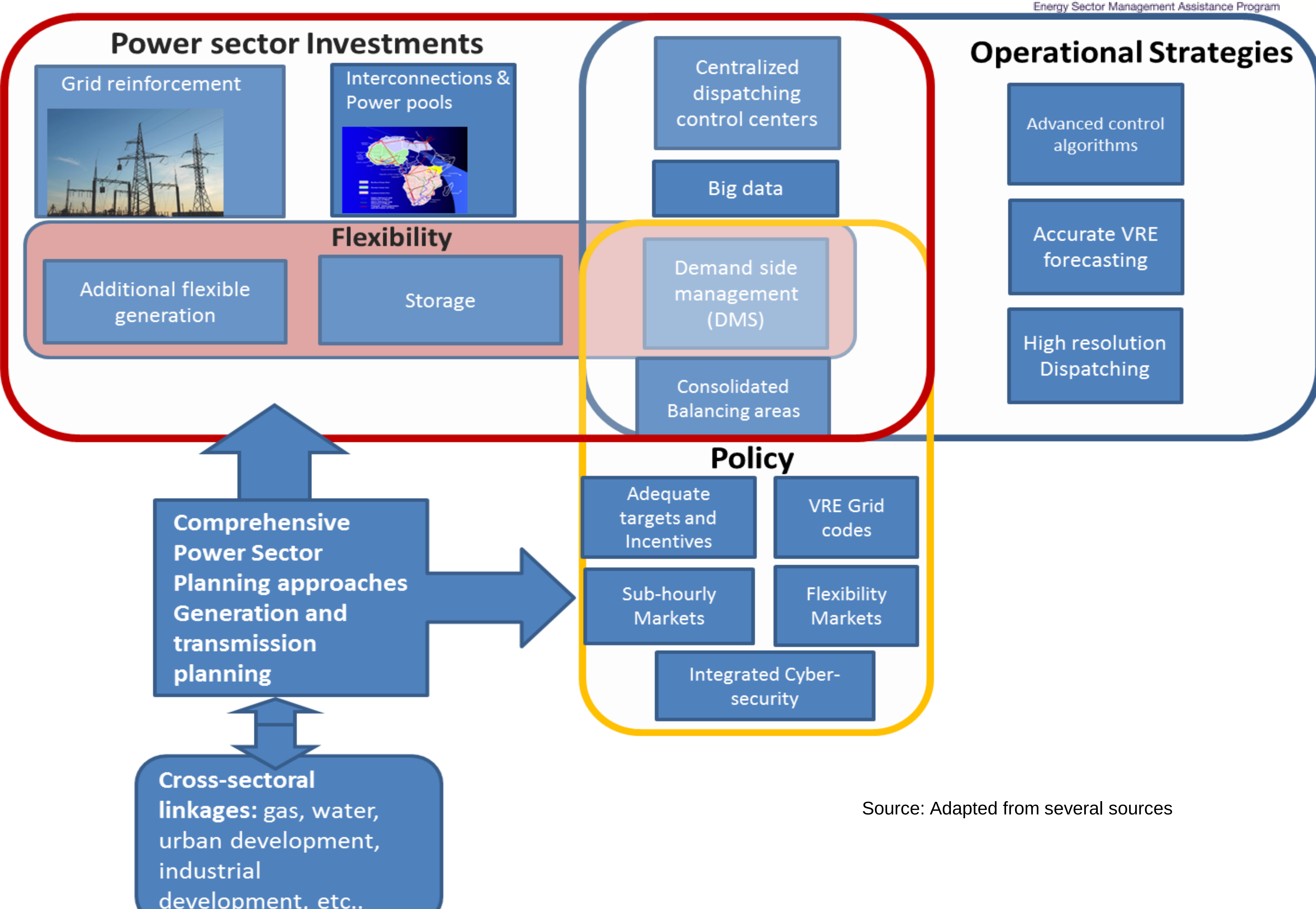
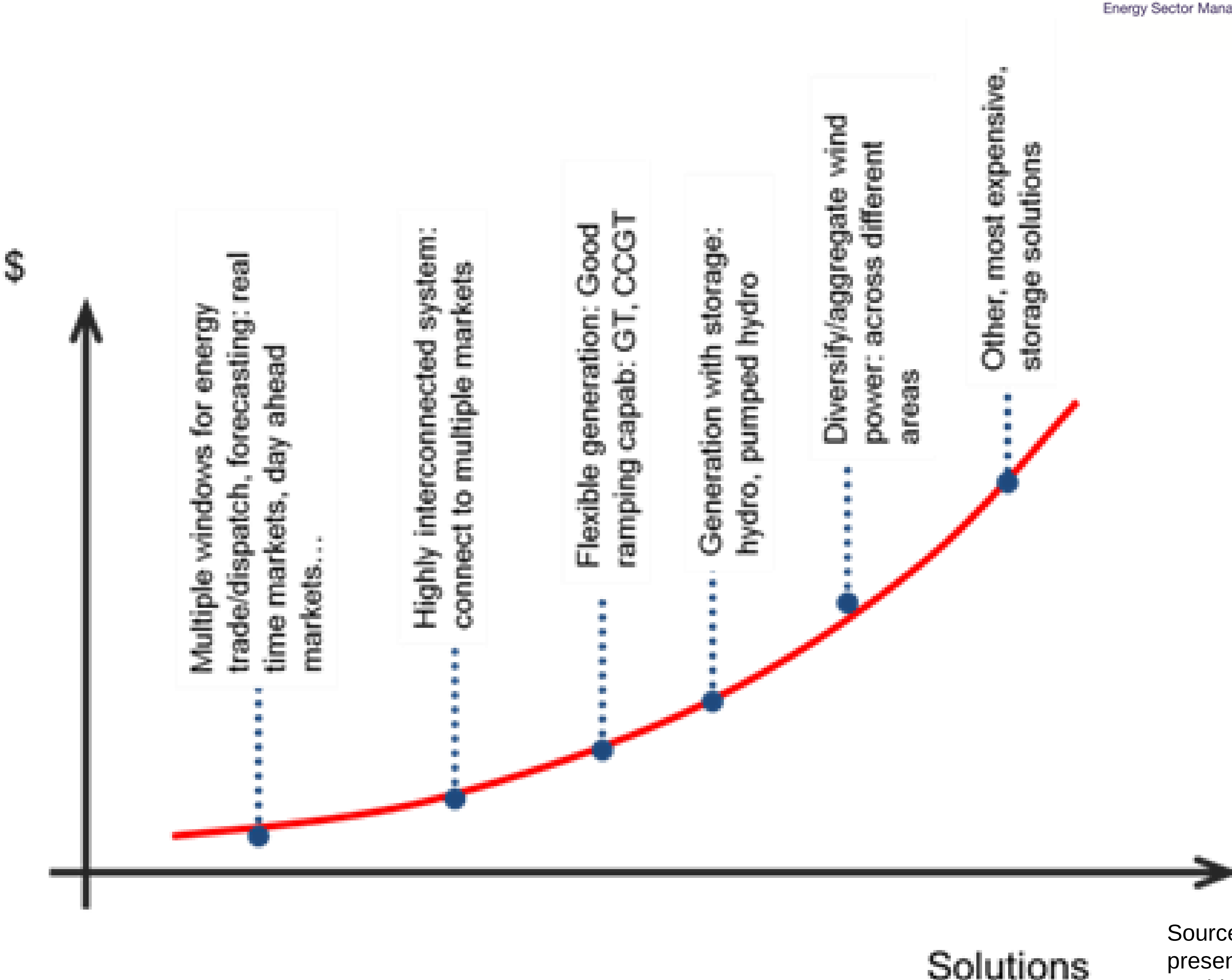
Integration solutions



Source: Adapted from several sources

Integration solutions

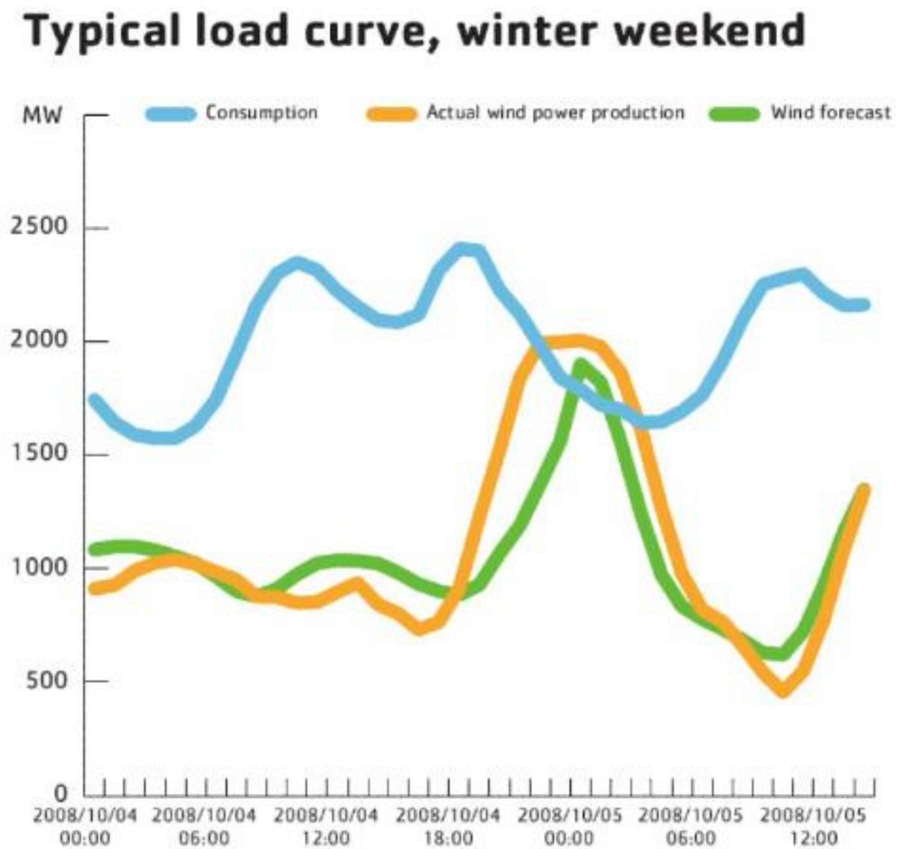


Source: Adapted from presentation by Marcelino Madrigal that World Bank.

Integration solutions

Interconnections and consolidation of Balancing areas

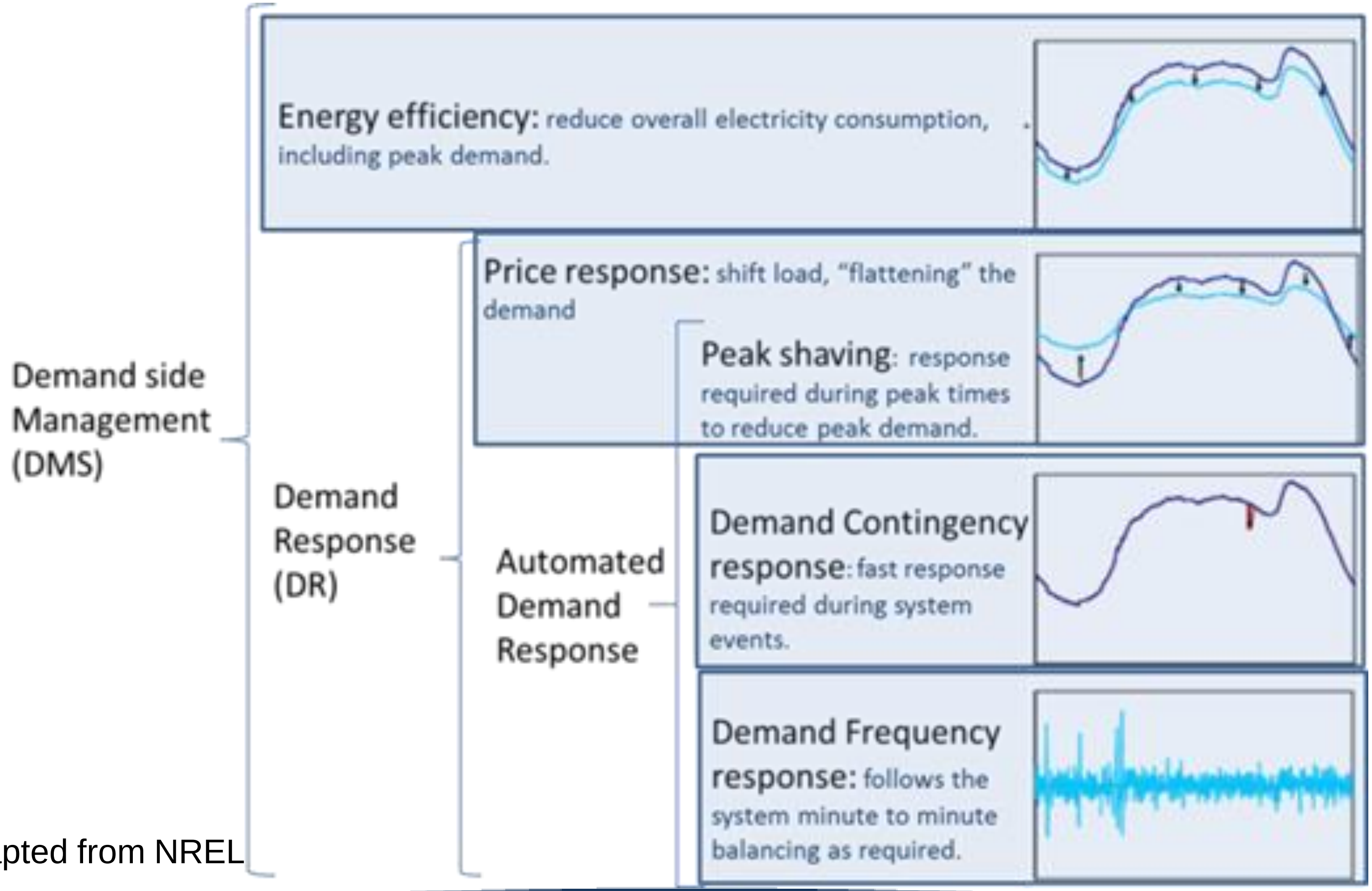
- During high wind conditions: excess traded to NORDEL or Germany
- During rapid wind decrease, large balancing area permit imports from Germany
- Grid stability is improved by interconnections



Source Energinet.dk
Denmark's TSO

Integration solutions

•**Demand Side Management** **Utilities provide incentives to electricity customers to reduce their consumption during periods of peak demand.**



Source: Adapted from NREL

Integration solutions

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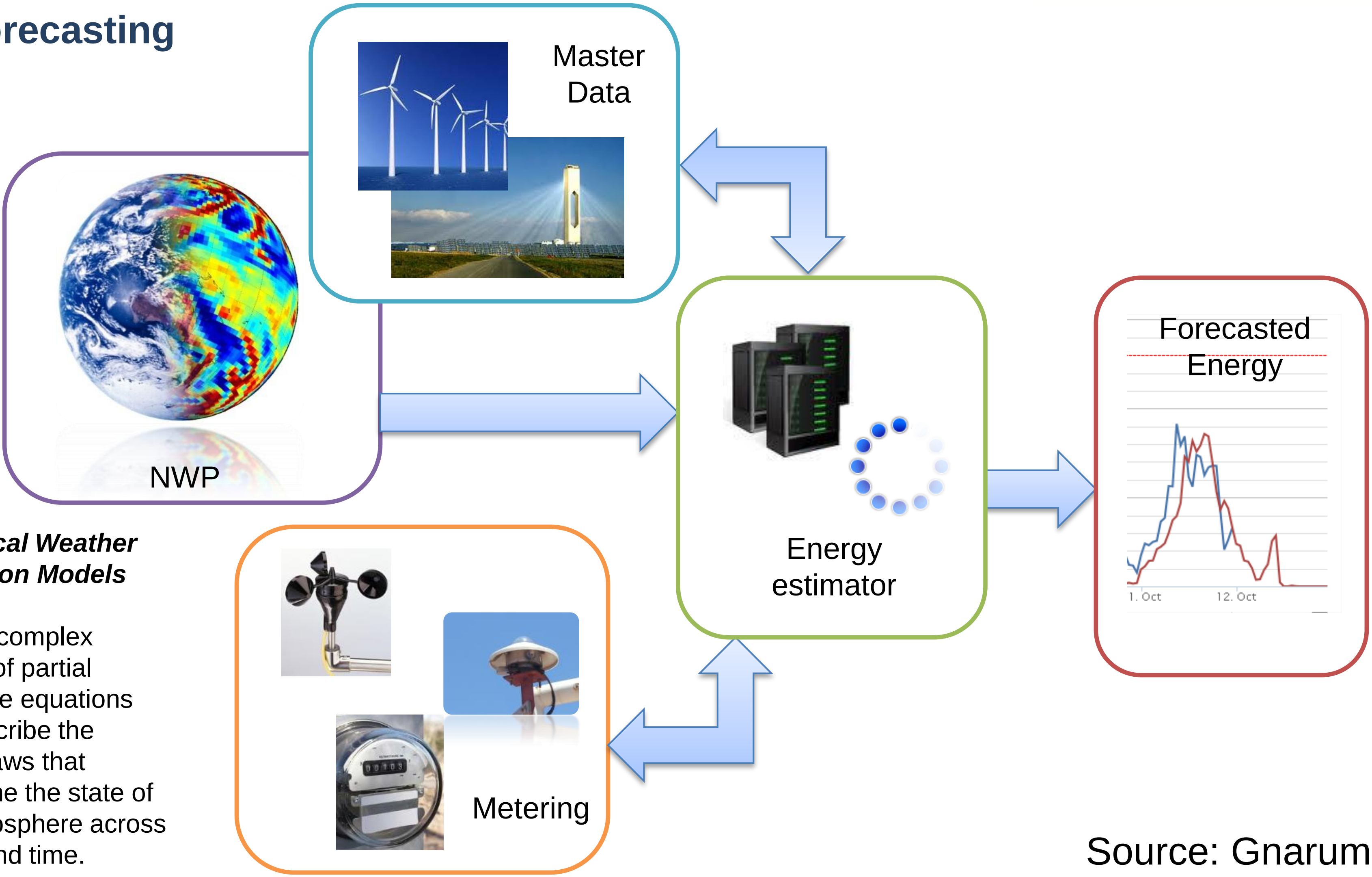
- **Forecasting**



Numerical Weather Prediction Models (NWP)
Solve a complex system of partial derivative equations that describe the physic laws that determine the state of the atmosphere across space and time.

Source: Gnarum

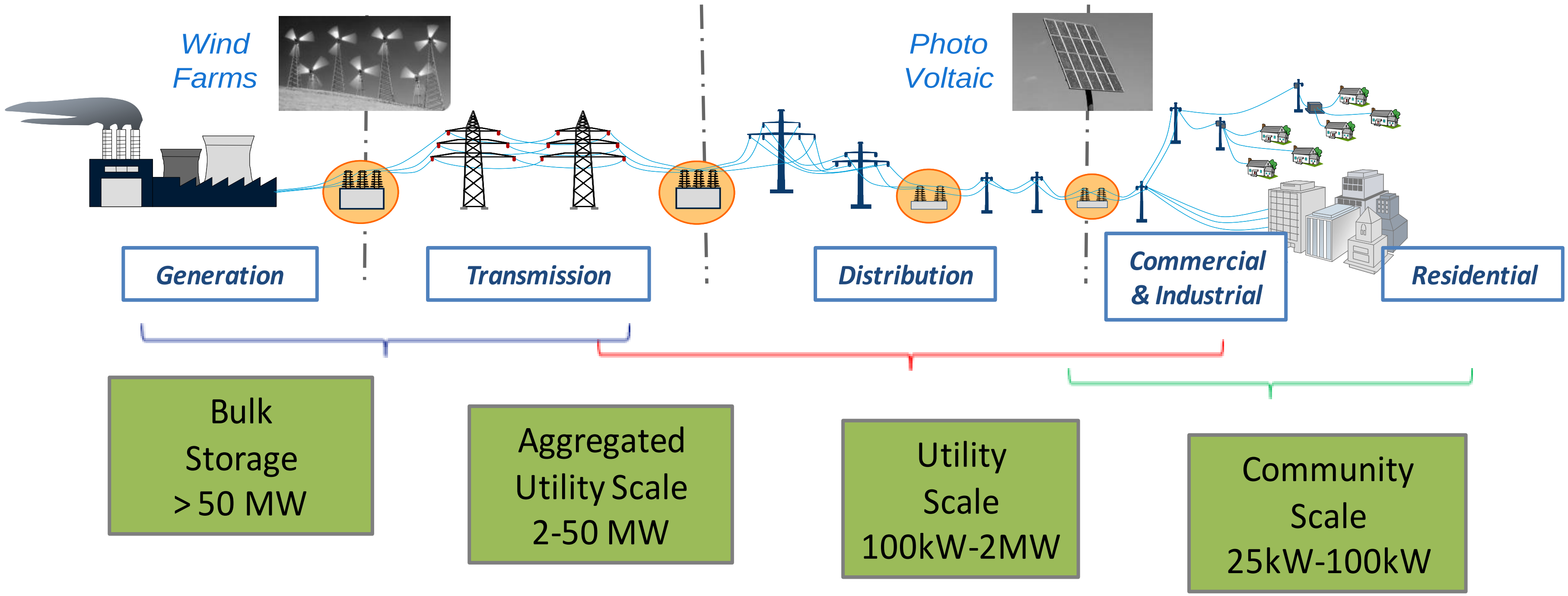
Integration solutions

Gas based generation

NG Generation Technology	Operational characteristics	Maintenance	Availability of vendors	Capital Costs ($/kW)
Microturbines	Operating Modes: Peak shaving, base load, stand-alone, standby or, primary power Turndown ratio: 10% Ramp-up rate: 10 sec Efficiency: 25-35% (new efficient designs claim 50%)	Very low fixed costs: 6-10 $/kW Variable cost: 2-4 c$/kWh	Limited: Capstone, Turbec Flex Energy, DREser-Rand.	2,000-3,500
Fuel Cells	Limited operability Turndown ratio: 50% Ramp-up: 2-5 hours Efficiency: 42- 50%	Maximum operating life: 15-20 years. Variable cost: 2-3 ¢$/kWh	Very limited: UTC Power, Fuel Cell energy, Ballard Power and Bloom Energy *Some manufacturers limit their market to US	5,500 – 7,500
Reciprocating Engines	Operating Modes: Base load, part load, peak shaving, load follow Turndown ratio: 50% Ramp-up rate: 5-15 min Efficiency: 28- 38%	Fixed costs range: 12-17 $/kW Variable cost range: 0.7-1.1 c$/kWh	Wide range of vendors: Wärtsilä, Caterpillar, Inc., GE, Cummins. Inc.	800 – 1,400
Gas Turbines (open cycle)	Operating Modes: peak shaving, base load, stand-alone, standby, primary power. Turndown ratio: 50% Ramp- up: 10-30 min Efficiency: 22- 44%	Fixed costs range: 14 – 16 $/kW Variable cost range: 0.6-0.8 c$/kWh	Wide range of manufacturers: GE, Kawasaki, Solar Turbines, Alstom, Mitsubishi Heavy Industries, and Siemens…	900-2,500
Combined Cycle Plants	Operating Modes: peak shaving, base load, stand-alone, standby, primary power Turndown ratio: 0% Ramp up: 10-60 min Efficiency: 38- 44%	Fixed costs range: 30-40 $/kW Variable cost range: 0.7-1 c$/kWh	Several manufacturers	850-1500
Hybrid Power Plants	Ability to load follow. Ramp up and ramp down dependent on the technology and the	Major equipment used have an operating life in the 15 – 30 year	Several manufacturers	Depends on technology

Integration solutions

Energy Storage

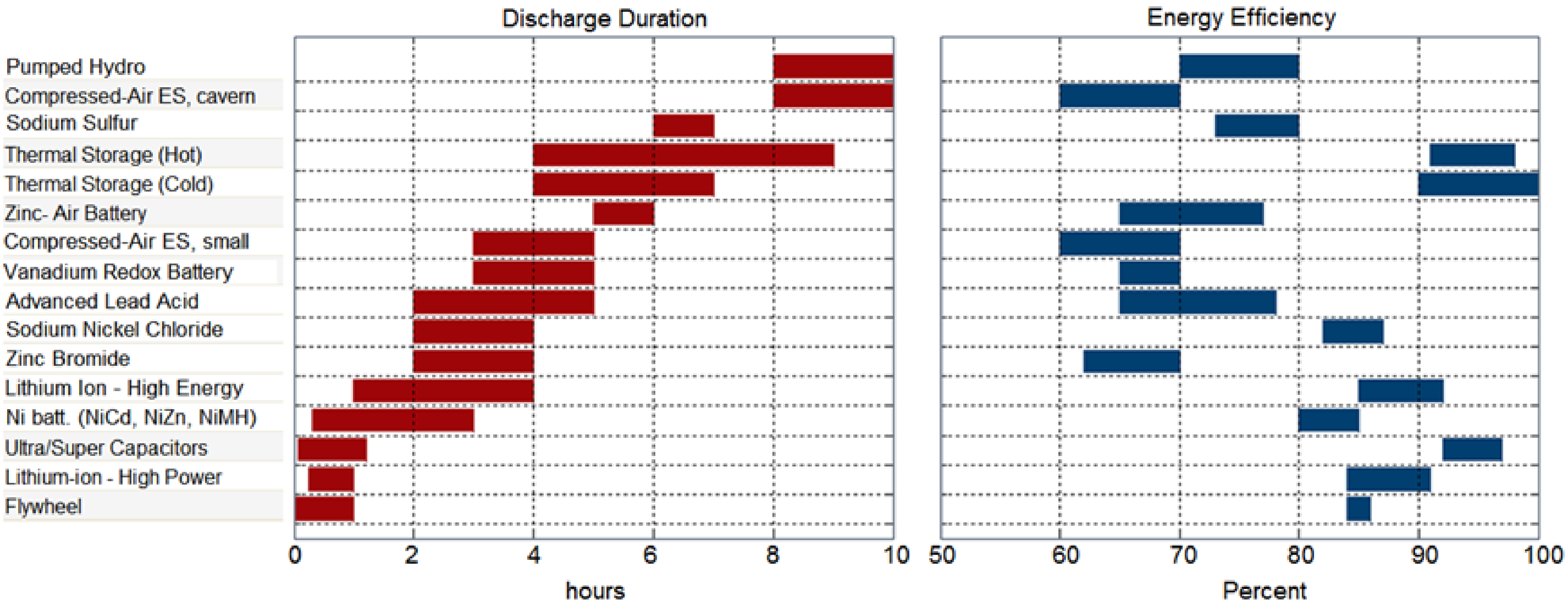


Source: KEMA

Does Energy storage compete with Interconnections?

Integration solutions

Energy Storage



Source: KEMA

Integration solutions

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Energy Storage

Technology option	Maturity	Capacity (MWh)	Power (MW)	Duration (hours)	% Efficiency (total cycles)	Total cost ($/kW)	Cost ($/kWh)	Advantages	Disadvantage
Technologies for Bulk Energy Storage to Support System and VRE Integration									
Pumped Hydro	Mature	1680-14000	280-1400	6-10	80-82 (>13000)	1500-4300	250-430	High capacity, low cost	Site specific
CAES (underground)	Commercial	1080-3600	135-180	8-20	(>13000)	960-1250	60-125	High capacity, low cost	Special site Requirement, Need gas as fuel
Sodium Sulfur (NAS)	Commercial	300	50	6	75 (4500)	3100-3300	520-550	High power and energy densities, high efficiency	Production cost / safety concerns (addressed in design)
Advanced Lead-Acid	Commercial / Demo	200-400	20-100	4-5	85-90 (2200-4500)	1700-4900	425-980	Low capital cost	Limited Cycle Life when deeply discharged
Flow Batteries	Demo / R&D	250	50	5	60-75 (>10000)	1440-3700	290-740	High capacity	Low energy density
Energy Storage for ISO (Independent System Operator) Fast Frequency Regulation and VRE Integration									
Flywheel	Demo	5	20	0.25	85-87 (>10000)	1950-2200	7800-8800	High power	Low energy density
Li-ion	Demo	0.25-25	1-100	0.25-1	87-92 (>10000)	1085-1550	4340-6200	High power and energy densities, High efficiency	High production cost, RequiRE special charging circuit
Advanced Lead-Acid	Demo	0.25-50	1-100	0.25-1	75-90 (>10000)	950-1590	2770-3800	Low capital cost	Limited life cycle when deeply discharged
Energy Storage for utility T&D grid support applications									
CAES (Aboveground)	Demo	250	50	5	(>10000)	1950-2150	390-430	High capacity, lowest cost	Special site Requirement, Need gas as fuel
Advanced lead acid	Demo	3.2-48	1-12	3.2-4	75-90 (4500)	2000-4600	625-1150	Low capital cost	Limited Cycle Life when deeply discharged
Sodium sulfur	Commercial	7.2	1	7.2	75 (4500)	3200-4000	445-555	High power and energy densities, high efficiency	Production cost / safety concerns (addressed in design)
Flow batteries	Demo / R&D	4-50	1-10	4-5	60-75 (>10000)	1200-3310	300-1350	High capacity	Low energy density
Zn/air	R&D	5.4	1	5.4	75 (4500)	1750-1900	325-350	Very high energy density	Electric charging is difficult
Li-ion	Demo	4-24	1-10	2-4	90-94 (4500)	1800-4100	900-1700	High power and energy densities, High efficiency	High production cost, RequiRE special charging circuit

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Conclusions

- Transmission is the most important barrier to scale-up renewables.
- VRE pose challenges to the grid operators due to variability and uncertainty , but solutions are available to allow high levels of VRE penetration.
- Efficient integration of VRE requires grid operators to have access to a proper mix of flexible resources ranging on the supply-side, delivery-side and demand-side.
- The best solution or set of solutions is very country specific.
- Advanced planning can help to reduce the integration costs by adding transmission capacity and interconnections, incorporating flexibility in the system during the least cost planning process and minimizing the amount of stranded generation assets.
- Interconnection standards prevent many VRE issues.