Economic and Social Commission for Western Asia

Integration Costs of Wind and Solar Power

July 30-31, Amman, Jordan

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Introduction

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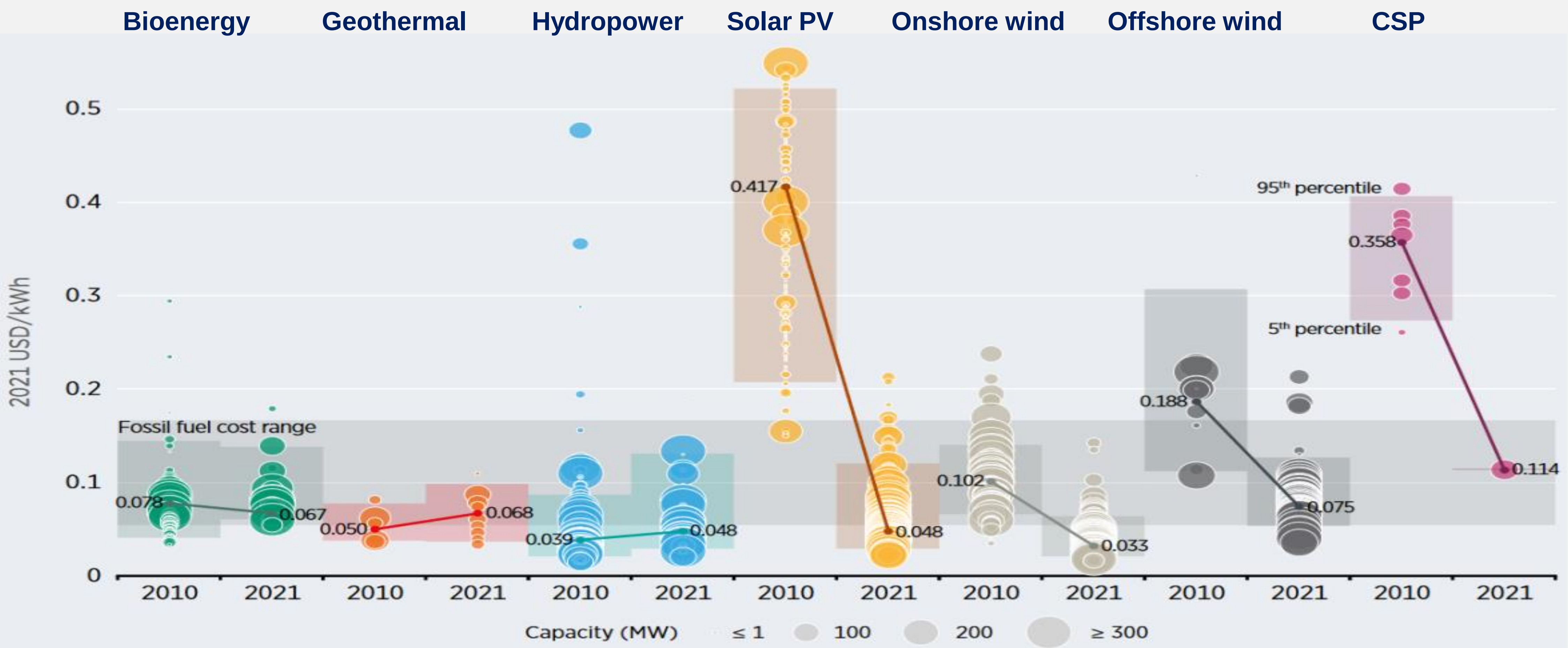
Motivation for Higher Renewable Energy Generation

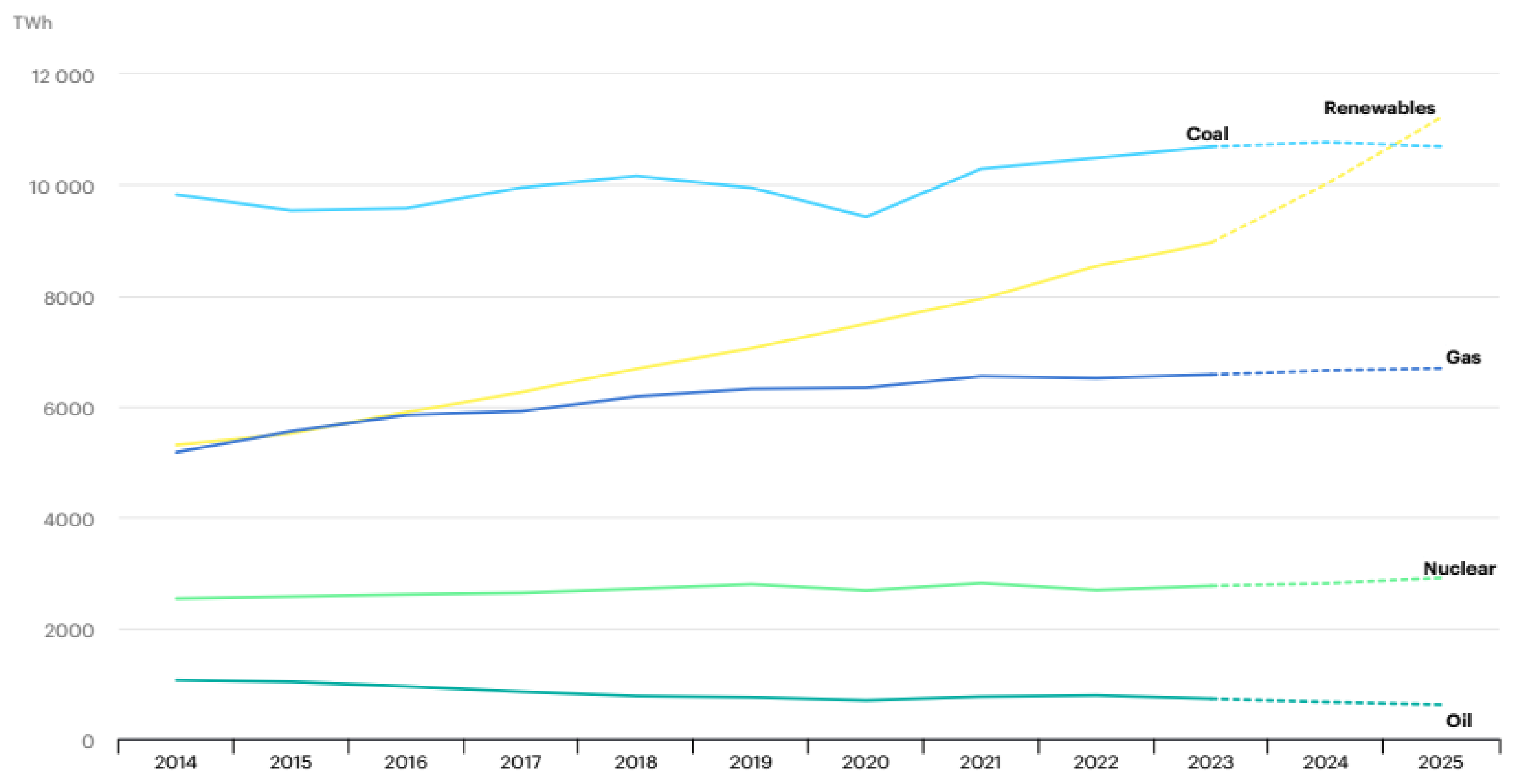
Key aspects

- Renewable energy (RE) is a key component in governments’ sustainable energy policies and climate ambitions with clear and measurable targets
- RE generation capacity represents the majority share of new additions globally
- Diversifying energy mix
- Improve energy access
- Job creation and economic growth
- Low cost of electricity (COE) option to serve growing demand

Global average COE from recent RE projects



Global electricity generation



https://www.iea.org/data-and-statistics/charts/total-annual-energy-investments-by-development-financial-institutions-by-region-2013-2022

Sample RE targets from select Arab countries

Country	Target (%)	Target Year
Morocco	52	2030
Saudi Arabia	50	2030
Egypt	42	2035
Iraq	40	2045
Algeria	30	2030
Jordan	30	2030
Tunisia	30	2030
Palestine	20	2030
Oman	10	2025

Challenges with Renewable Energy Generation

Challenges with renewable energy generation

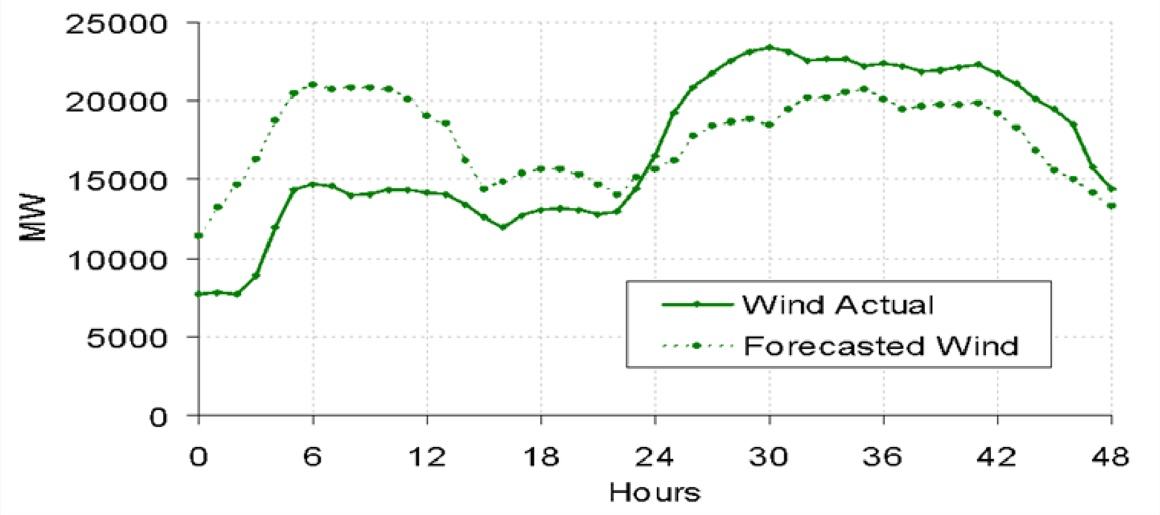
- **Inverter-based, non-synchronous generators:** Do not have the same response as synchronous generators to ensure grid stability
  - Large voltage variations
  - Loss of large blocks of wind generation after grid faults
  - Uncontrollable power from wind turbines
  - No inertial response
  - Inflexible operation strategies during light load and high-risk periods

- **Uncertainty and Variability**: Need other resources to balance the system

Uncertainty vs. Variability

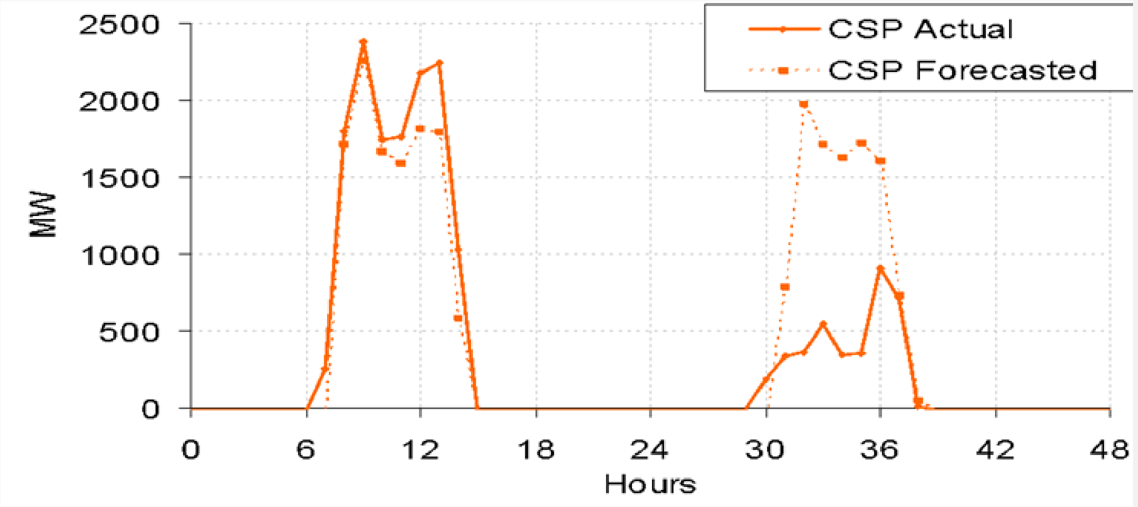
Uncertainty

- Wind and solar generation are not always available when called upon
- They are not dispatchable … output is predicted by a forecast
- Actual power output is different than forecast output



Variability

- Wind and solar generation vary as the intensity of their energy sources
- Several timescales … minute (regulation), hour (ramping), daily, seasonal



A perfect forecast eliminates uncertainty, but variability remains

Interconnection issues and dynamic performance

Voltage Regulation

- Dynamic voltage response
- Flicker

Regulator Coordination

- Voltage droop
- Reactive power sharing

Active Power Control

- Frequency regulation
- Intertie flow regulation
- Unit commitment

Stability

- Maintaining synchronism
- Damping
- Voltage stability

Fault Tolerance

What makes wind/solar plants different?

- **“Must Take” Resources:** Public policy goals in addition to marginal operating cost means that they are often first to be used.
- **Remotely located:** Need to build long transmission lines to load centers.
- **Grid Integration:** Integration economics, operating procedures, interaction with conventional resources.

Need to develop risk mitigation strategy

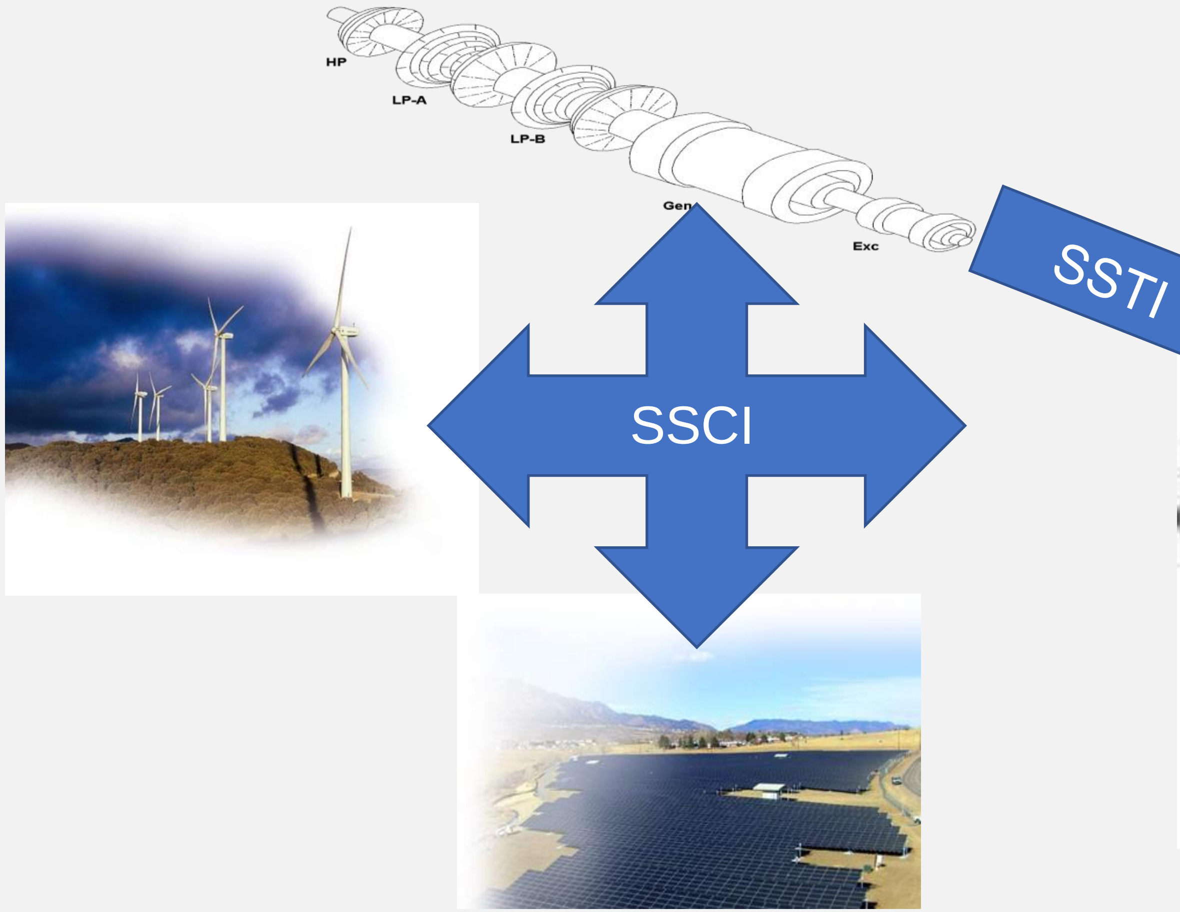
Conventional and power electronics

- **Long transmission corridors** (low system strength) typically have power transfer limited below thermal limits, due to stability challenges

Conventional Generation	Power-Electronic (PE) Sources
• Transient stability • Dynamic stability • Voltage stability	• Fast control stability • Voltage stability

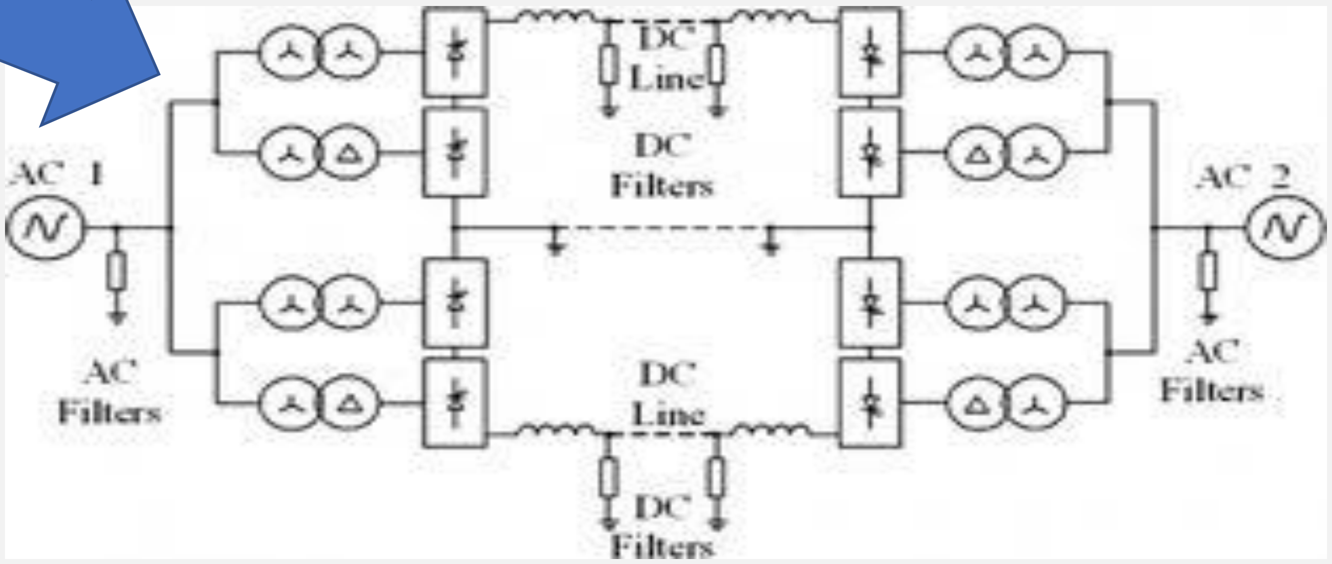
- **Fast control stability refers** to interactions between transmission system and PE sources (WTG controls, Invertors, HVDC, SVCs, STATCOMs, etc.)

Large STG, HVDC and RE interconnection



Sub-synchronous resonance is associated with the controls of generating units and other equipment

- SSTI : Sub-Synchronous Torsional Interactions
- SSCI : Sub-Synchronous Control Interactions



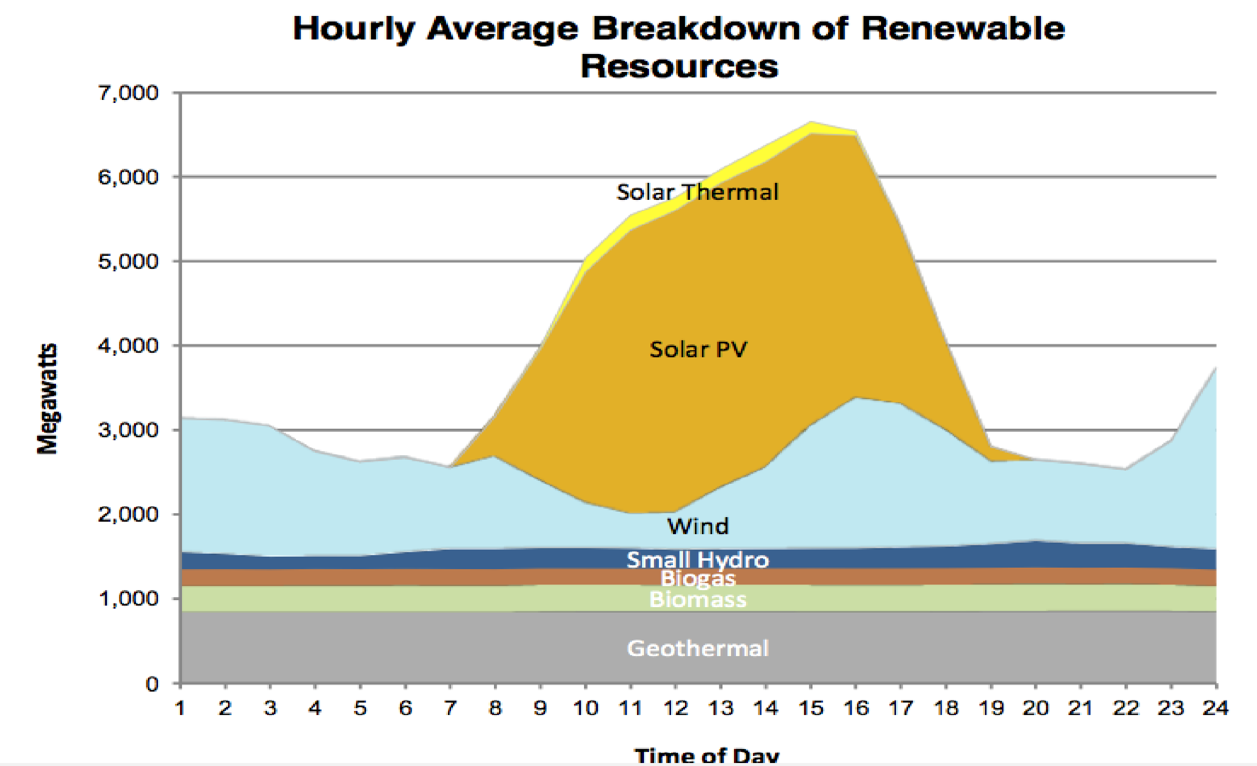
Availability of wind and solar

Solar

- Ramp management
- Large sunset/sunrise ramps
- Ability/willingness to decommit other units

Wind

- Ramp prediction
- With geographic diversity, relatively smaller ramps
- A willingness to hold more reserves



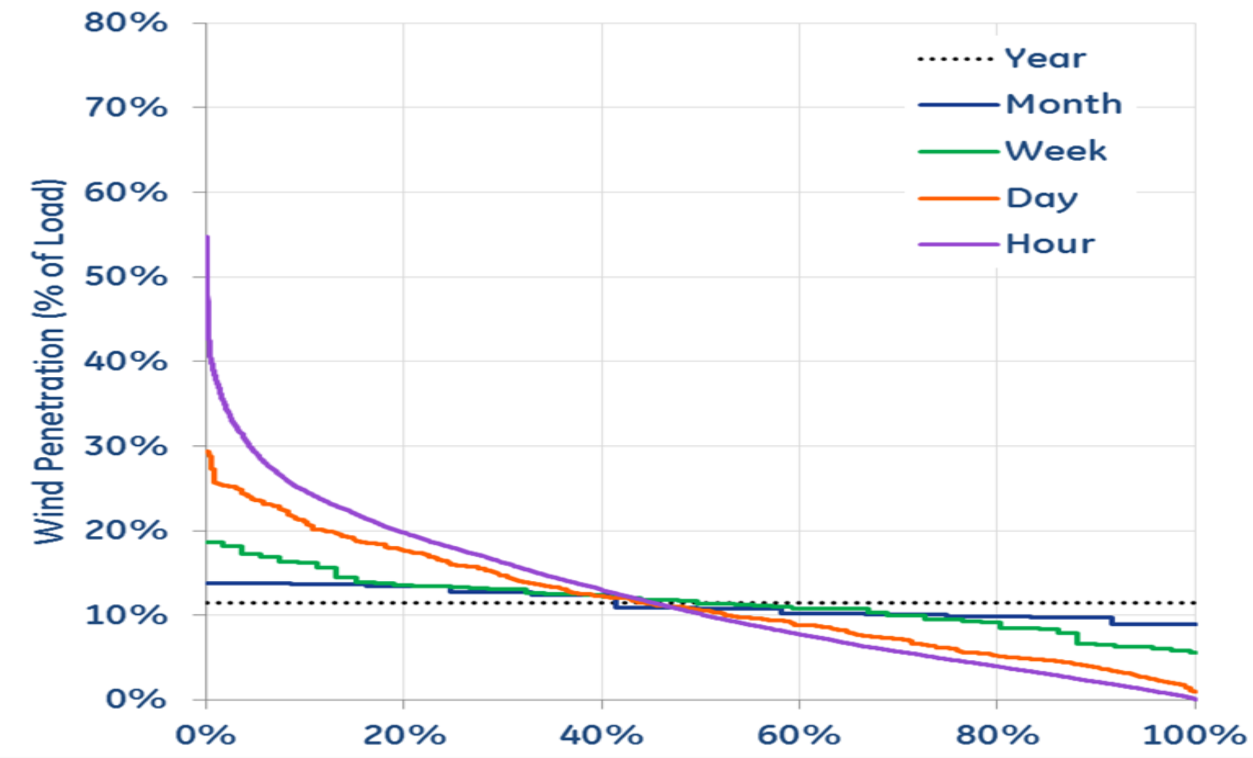
Source: CAISO Renewables Watch March 29, 2014

Wind and solar compliment each other

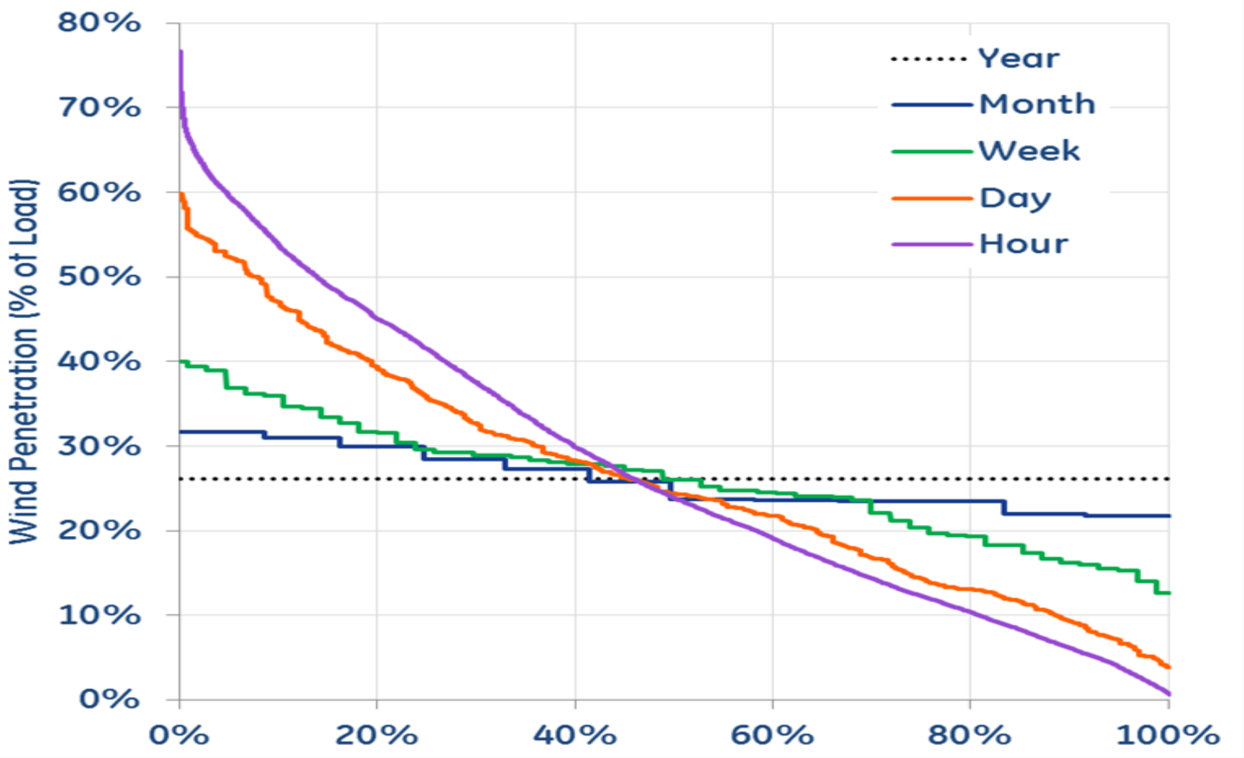
Operational impact of wind and solar

What does 30% penetration mean?

Nova Scotia: Base Case

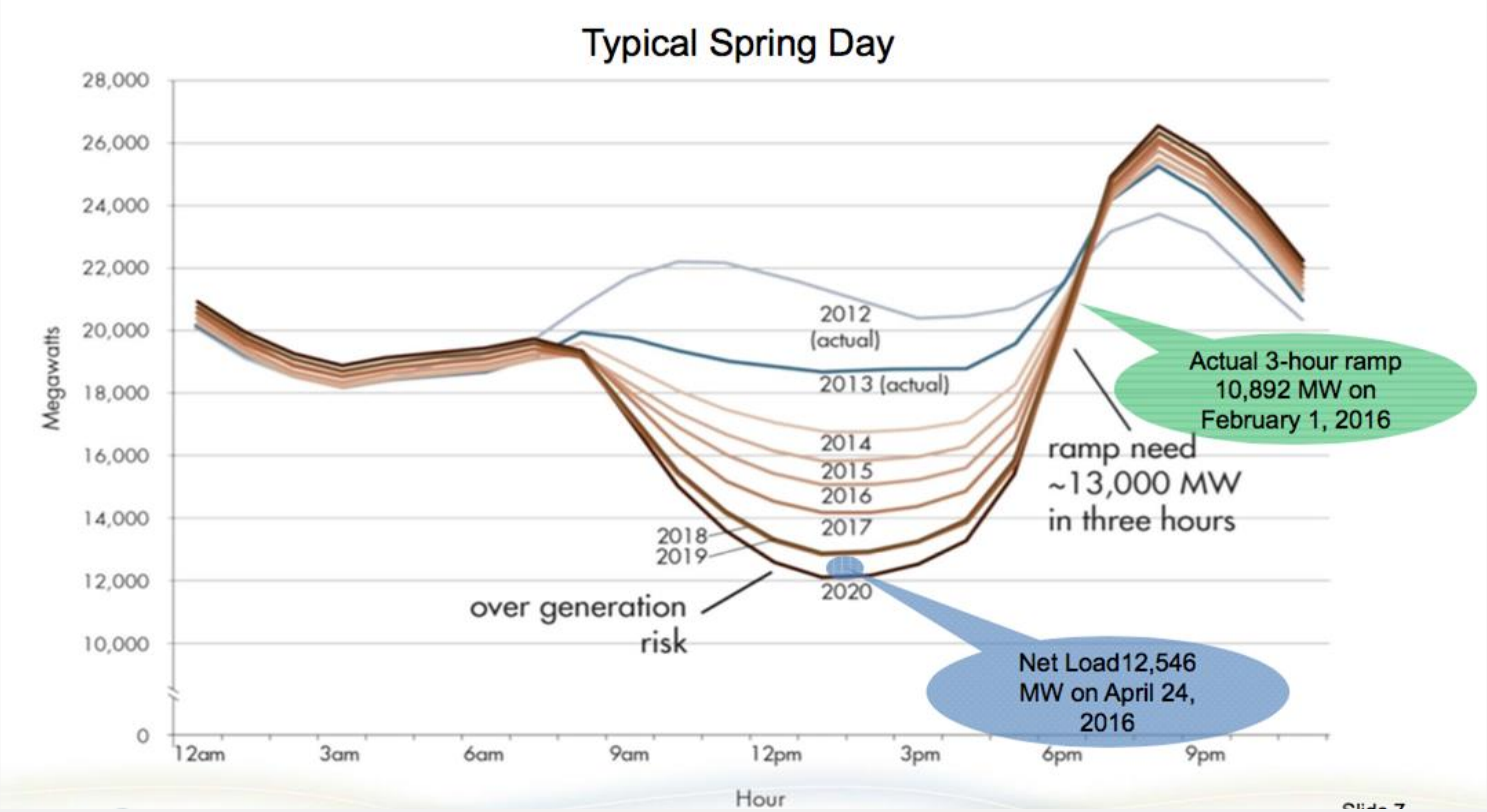


Nova Scotia: High Wind Case



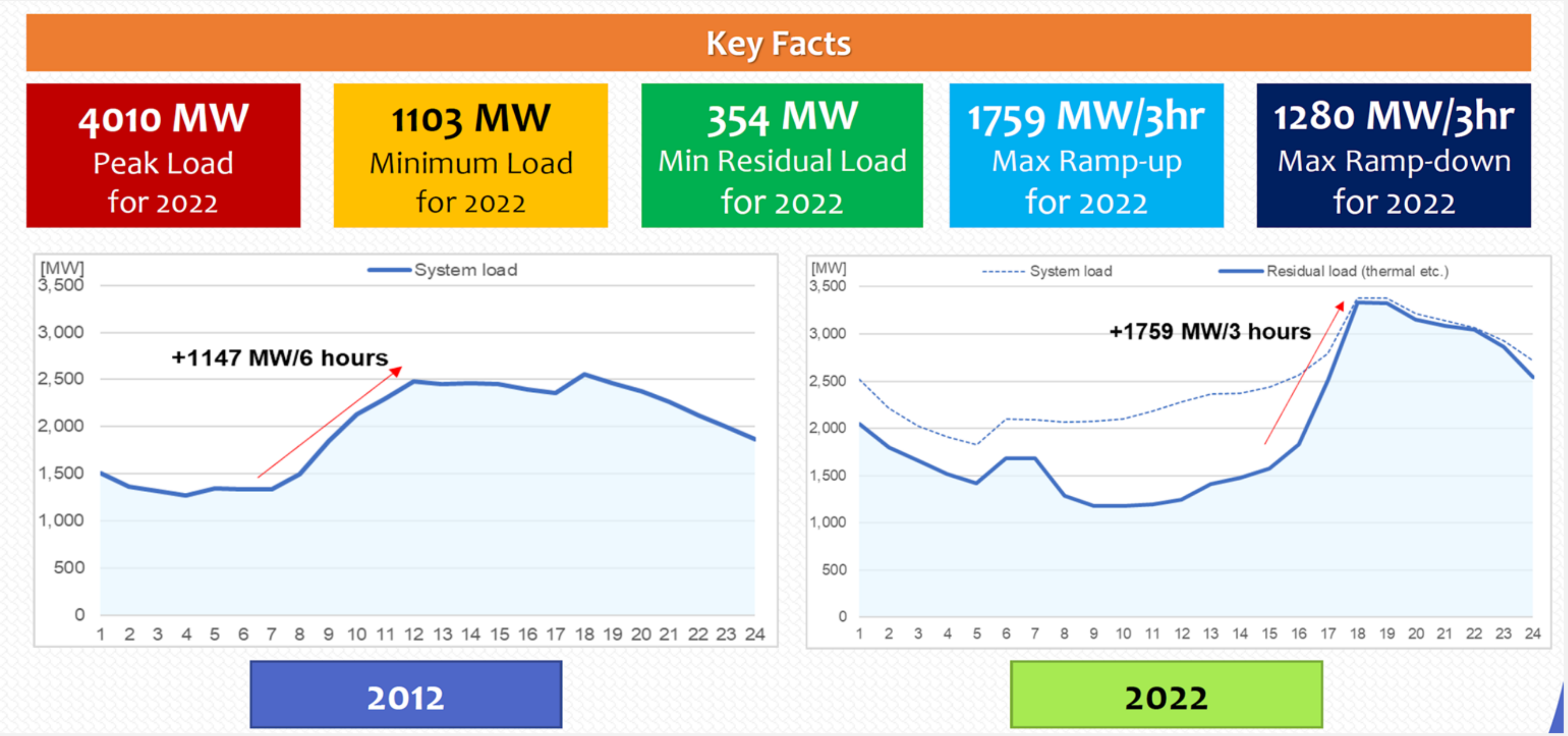
It is important to look at all time-frames of grid operation

Moving towards net load curve: The Duck curve



Source: Rothleder, CAISO 2016

Moving towards net load curve: The Duck curve



Key Facts

4010 MW Peak Load for 2022	**1103 MW** Minimum Load for 2022	**354 MW** Min Residual Load for 2022	**1759 MW/3hr** Max Ramp-up for 2022	**1280 MW/3hr** Max Ramp-down for 2022

Towards realization of the first PHES in Jordan (Source: NEPCO)

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Integration Economics

Financial aspects

- The LCOE for RE has reduced significantly over time. RE integration would attract some cost to manage the intermittent nature of RE.

- The range of cost estimates is largely a function of:
  - Geographical factors
  - The supply/demand correlation
  - Power system characteristics that determine the flexibility of operation

- It is widely accepted that:
  - The system integration cost are modest at low and intermediate shares of RE in many countries.
  - The system may demand development of very flexible electricity systems for a very high variable RE share which may attract large investment due to retrofits as well as new builds.

Integration costs

- Typically, three components are included under integration costs:
    1. **Costs (or benefits) from interaction with other power plants:** Most significantly, the increase in the specific costs of production of other power plants due to the reduction of their full load hours.
    2. **Grid costs:** Costs to bring the electricity to where it is needed.
    3. **Balancing Costs:** Costs to offset differences between forecasts and actual production.
- Each of these costs occurs when a new power plant is added to an existing power system – be it wind, solar or thermal.
- Due to their specific, weather-dependent generation profile, integration costs for wind turbines and solar PV differ from those of base load plants in several aspects.

Summary

- RE generation technologies offer the lowest cost of generation where wind and solar resources complement each other
- The grid needs support from other technologies due to higher uncertainty and variability RE generation
- RE technologies are likely to result in grid stability issues including sub-synchronous resonance (SSR) issues
- RE generation influences all the following areas:
  - Power generation
  - Transmission networks
  - Distribution networks
  - Grid operation and planning aspects
- It is important to understand the overall impact (technical as well as financial)
- Comparing the total system costs/value for different scenarios would be a more appropriate approach.

Questions?

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Integration Costs of Wind and Solar Power

Impact of RE on Power Generation

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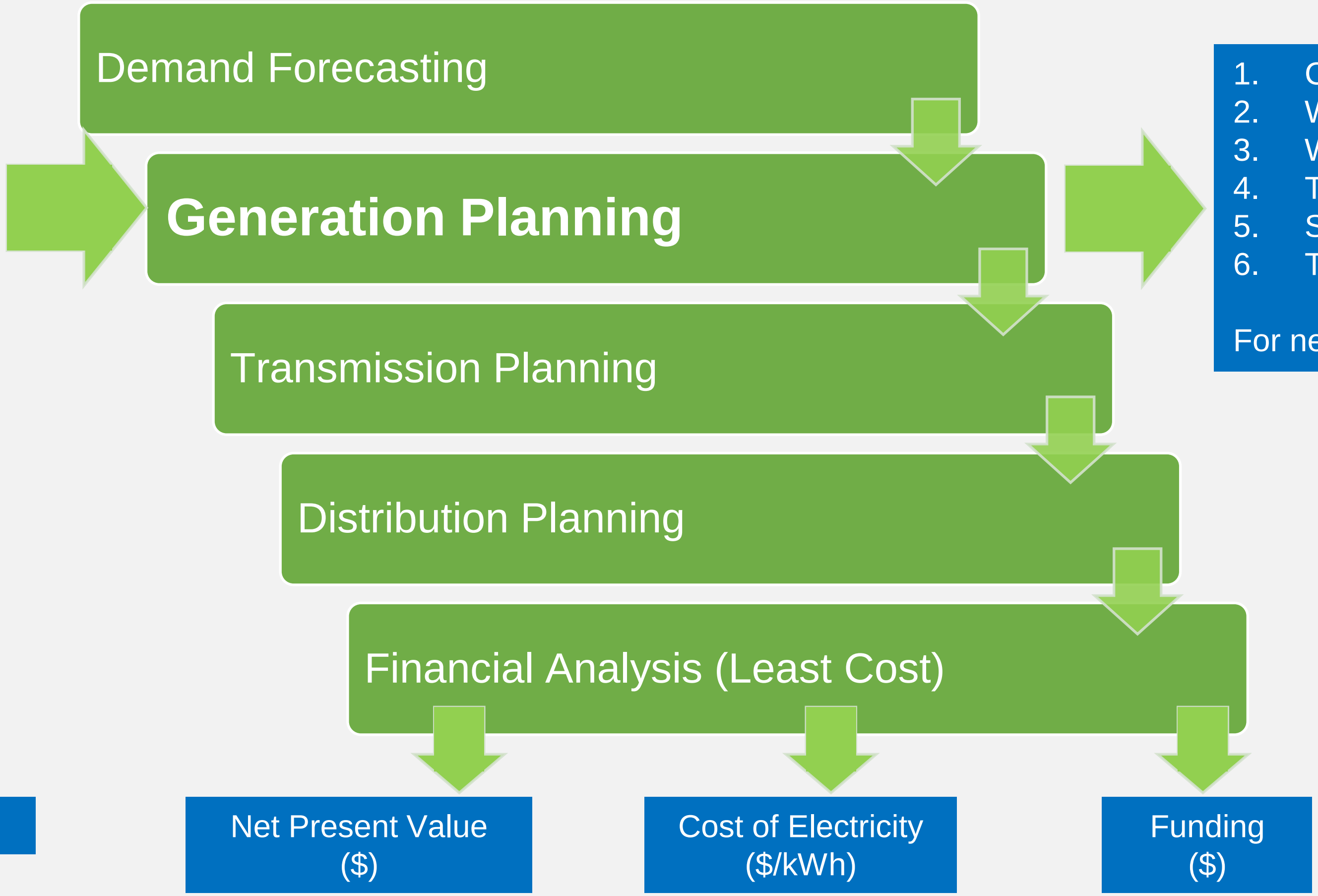
Planning and Operational Aspects

Generation planning

1. Existing fleet
2. Unit upgrades
3. Import from other countries
4. Technical inputs
   - Minimum loading
   - Ramp-rates
   - Start time
5. Reliability
   - Forced Outage Rate
   - Maintenance
6. Planned additions
7. RE Potential / Target additions
8. Fuel availability
9. Loss Of Load Expectation
10. Cost
    - Fixed cost
    - Variable cost
    - Start-up cost

Tools: PLEXOS, PROMOD, MAPS, etc.



Demand Forecasting

Generation Planning

Transmission Planning

Distribution Planning

Financial Analysis (Least Cost)

Net Present Value
($)

Cost of Electricity
($/kWh)

Funding
($)

1. Capacity to be added
2. When to add
3. Where to add
4. Type of generation
5. Surplus generation / Unserved load
6. Total system cost

For next 5,10,20,30 years

Capacity addition

- The typical average capacity factors (PLF) for different technologies is as follows:
  - Thermal (Gas/Steam) = 90%
  - WTG = 30%
  - Solar = 20%

- This means that the capacity needed to meet the same load demand (in energy terms):
  - If thermal (gas/steam) capacity addition is 100 MW,
  - Wind energy capacity addition should be 300 MW
  - Solar PV capacity addition should be 450 MW

More wind and solar capacities need to be built than thermal to meet the same load demand

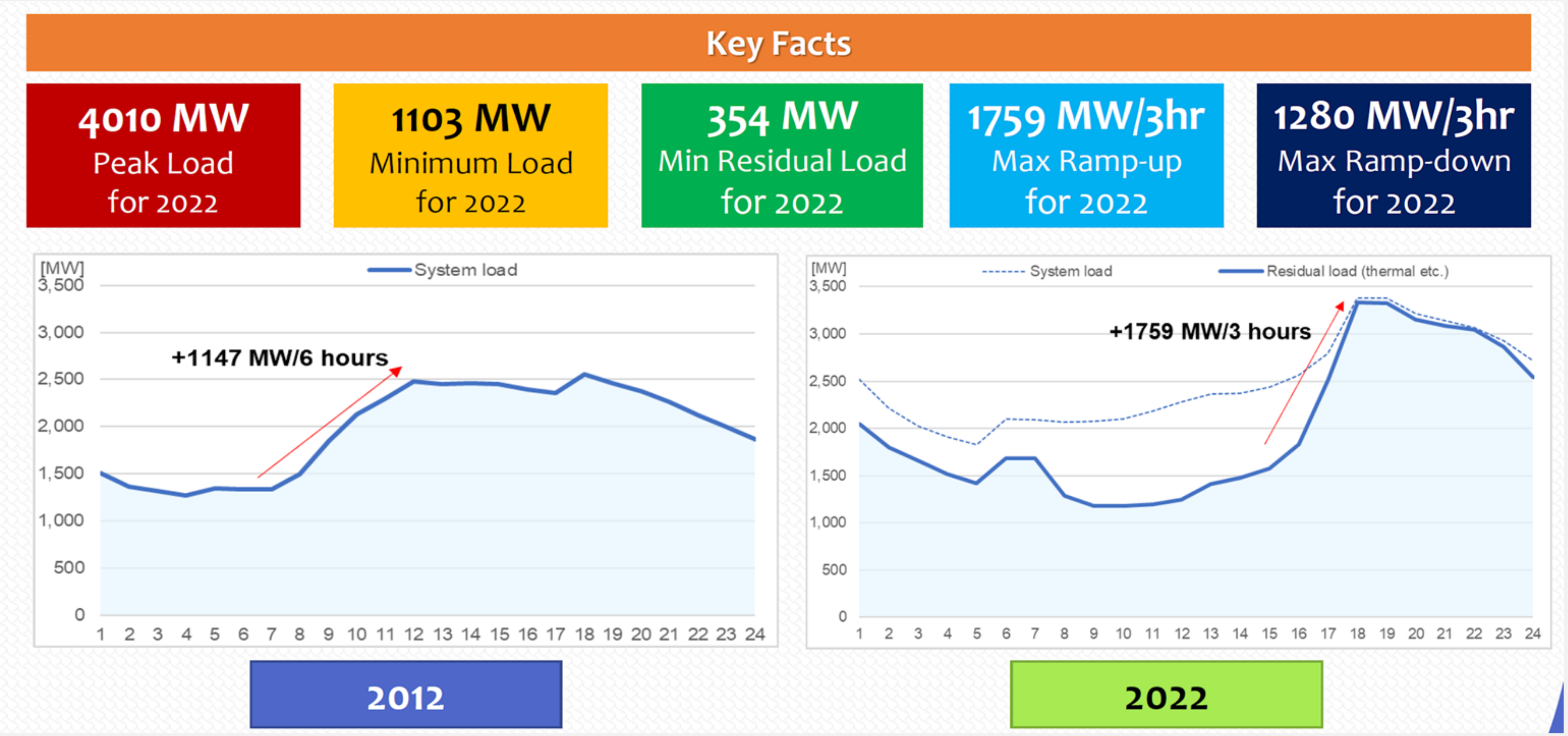
Capacity addition

- The average CAPEX per MW for different technologies is as follows:
  - Thermal (gas/steam) = US$ 0.60 M / MW
  - Wind energy = US$ 0.85 M / MW
  - Solar PV = US$ 0.85 M / MW

- This means that overall CAPEX requirement (for same MWh) would be:
  - Thermal (gas/steam) = US$ 60 M
  - Wind energy = US$ 255 M
  - Solar PV = US$ 383 M

Wind and solar need higher CAPEX

Moving towards net load curve: The Duck curve



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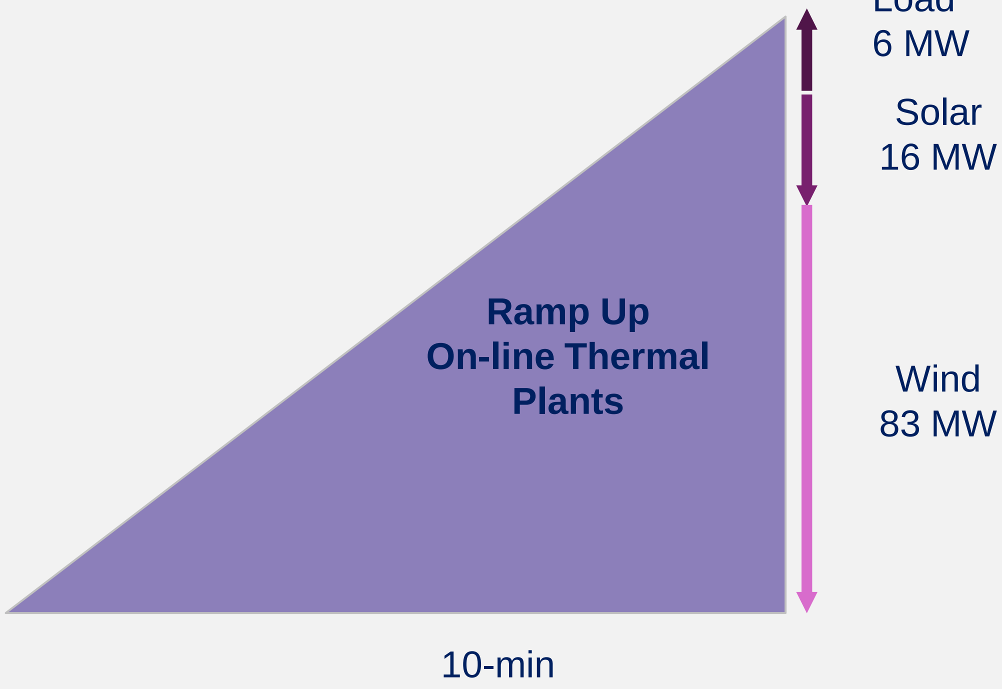
Towards realization of the first PHES in Jordan (Source: NEPCO)

Importance of flexible resource

Large wind drop, solar drop, and load rise



Ramp Up
On-line Thermal Plants

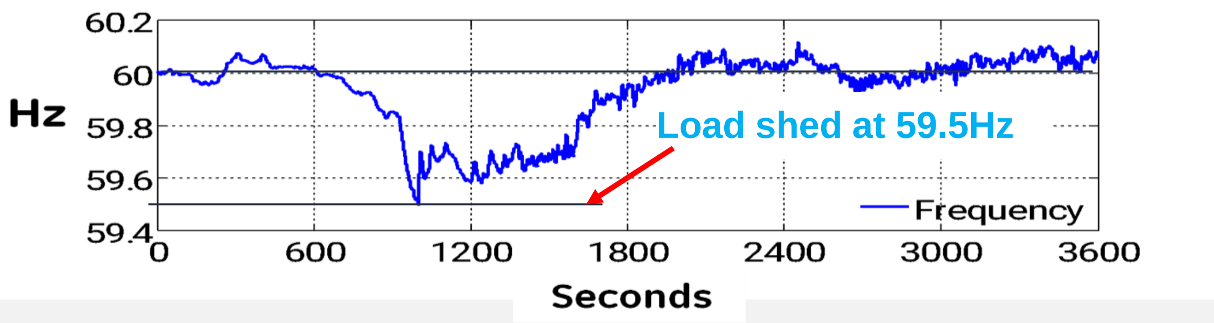
Load
6 MW

Solar
16 MW

Wind
83 MW

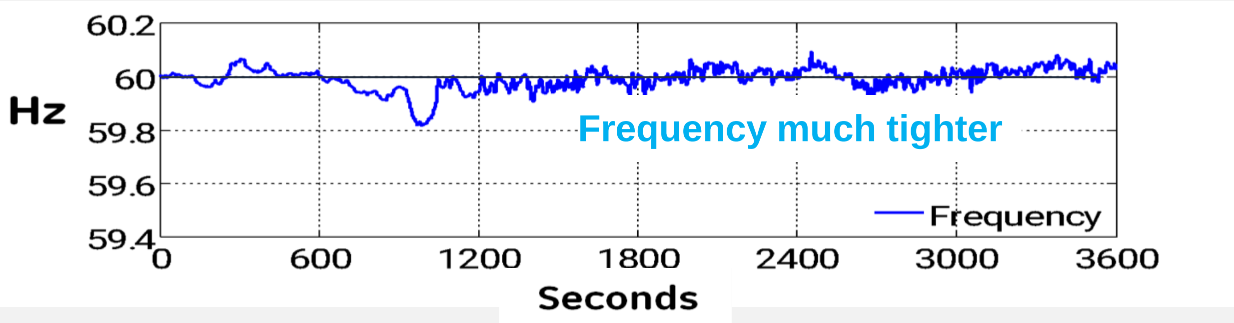
10-min

Today's Ramp Rates / Droop



Load shed at 59.5Hz

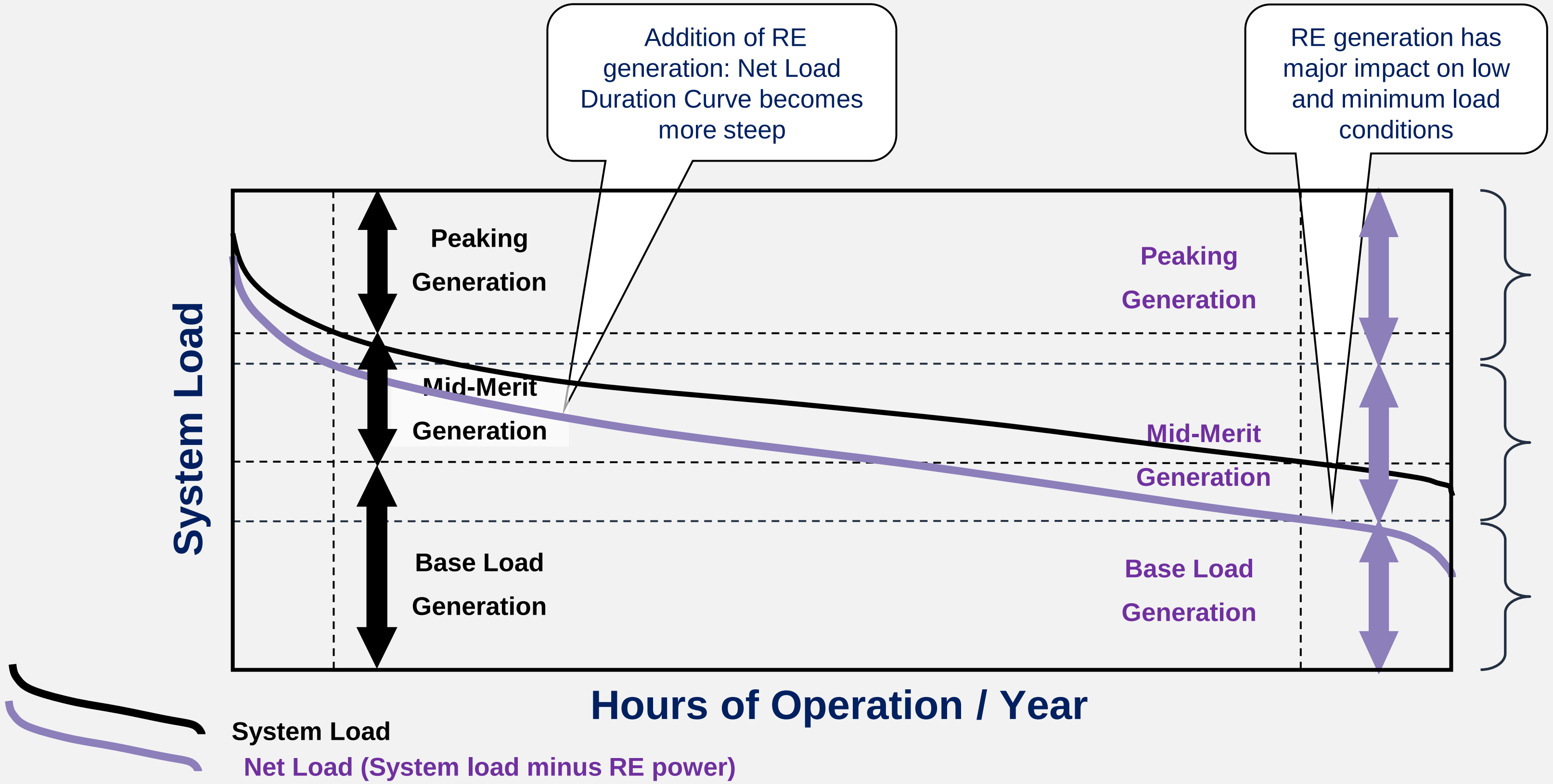
Proposed Future Ramp Rate / Droop



Frequency much tighter

Effective ramp rate control can support the grid effectively

Impact on load duration curve due to higher RE



Addition of RE generation: Net Load Duration Curve becomes more steep

RE generation has major impact on low and minimum load conditions

Emerging Flexible Resources

BESS

Gas SC

Hydro

Smart Grid

Gas CCGT

Clean Coal

Nuclear

Significant shift in operational philosophy of power plants … More weather dependent

Importance of Reserve Margin

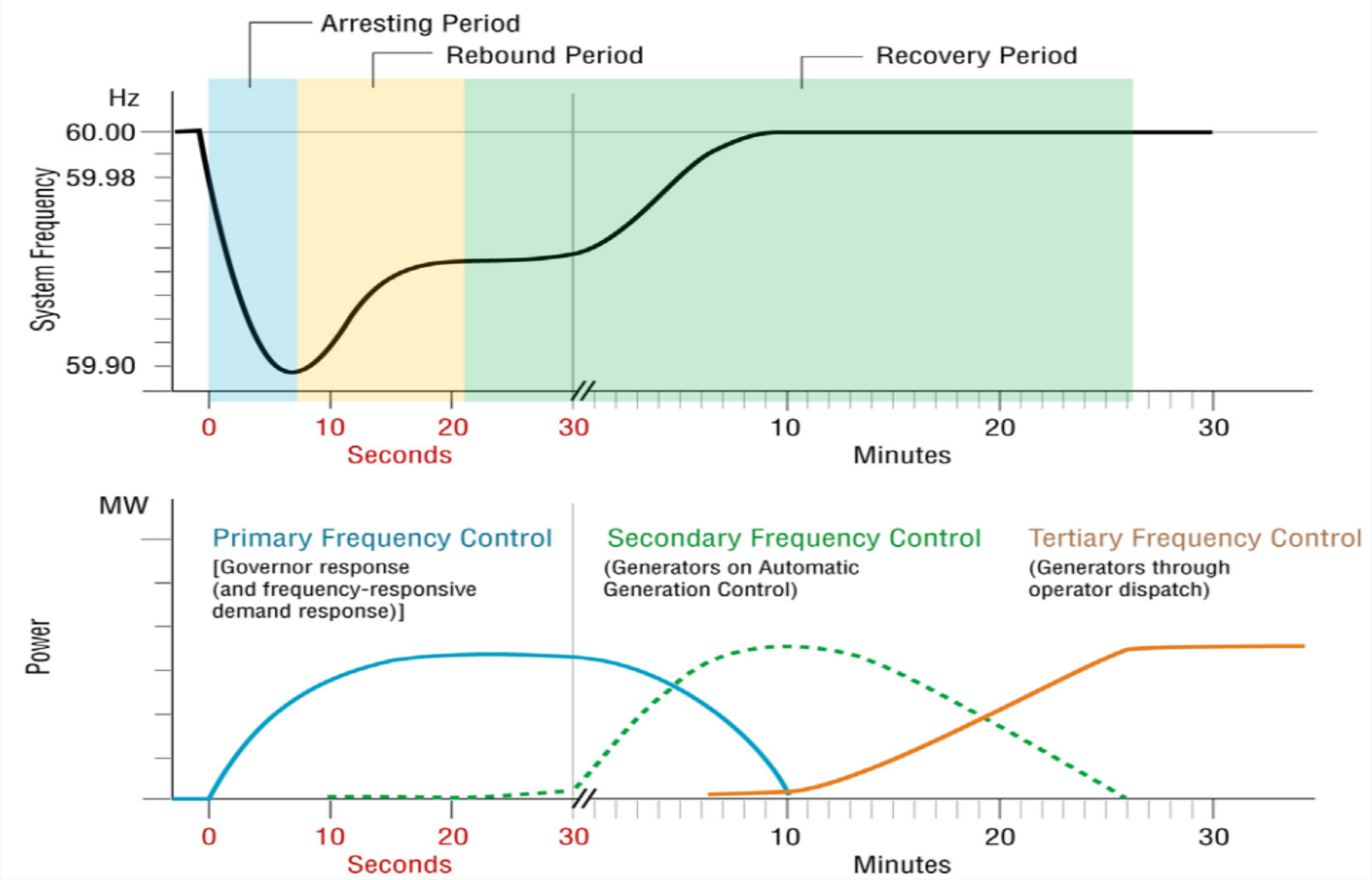
Reserve margin

- **Reserve Margin:** Defined as the percentage difference between the total available generation capacity and the forecasted peak demand i.e. "reserve" that is available beyond the peak demand.

$$RM(^0/_0) = \frac{(AC-PD)}{PD} \times 100$$; RM = Reserve Margin, AC = Available Capacity, PD = Peak Demand

- **Planning Reserves:** Additional generation capacity that are planned and procured in advance.
  - To meet future demand growth
  - Considering retirements of existing assets
  - Based on changes in regulatory requirement
- **Operating Reserves:** Additional extra generation capacity or energy that is available at short notice
  - To balance supply and demand
  - Contingency management
  - Maintain grid stability (Includes RE variability)

Frequency Response



Source: LBNL Report on Frequency Response Metrics

- **Primary Frequency Control**
  - Response Time: Seconds
  - Control: Automatic
- **Secondary Frequency Control**
  - Response Time: Minutes
  - Control: Automatic / Manual
- **Tertiary Frequency Control**
  - Response Time: 10-15 Minutes
  - Control: Manual

Role of operating reserves

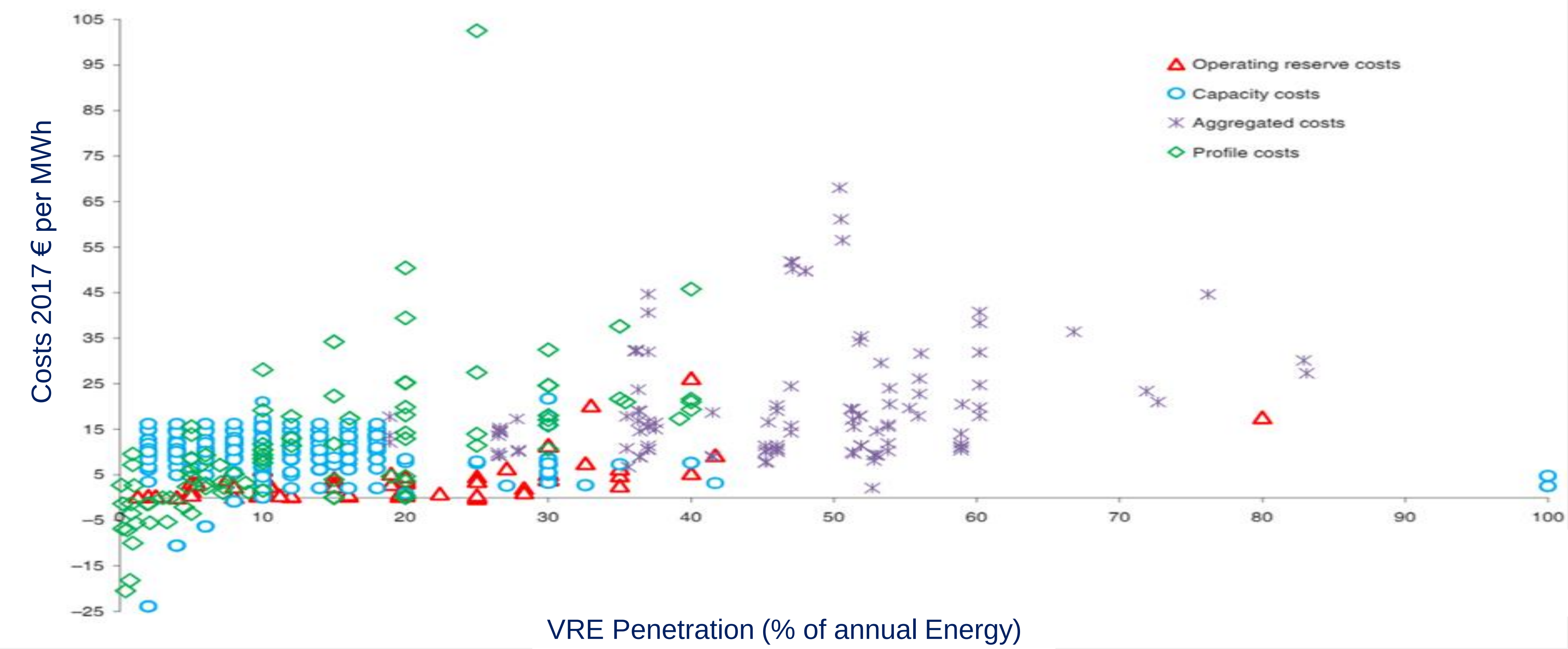
- **Primary, Secondary and Tertiary reserves:** These shall be deployed for the purpose of frequency control, reducing area control error and relieving congestion.
  - The response under Primary reserve shall be provided as per the regulations.
  - Secondary reserves including automatic generation control (AGC) and demand response shall be deployed by control areas.
  - Tertiary reserves shall be deployed by a control areas as per the regulations.
- **Black Start reserves:**
  - Generating stations with black start capability to be identified as black start reserves.
- **Voltage Control reserves:**
  - Have gained more importance due to limited reactive power support from RE sources.
  - These shall be deployed at a bus through reactive power injection or drawl.

How much operating reserves the grid requires?

- Determining the adequate amount of spinning reserve depends on:
  - Power system's reliability (LOLE) targets
  - Largest contingency (depends on largest generating unit, transformer (large capacity), transmission line with largest capacity, largest import, largest load, etc.)
  - RE forecasting error (wind as well as solar)

- General approach:
  - Maintain spinning reserve levels equivalent to 10% to 15% of the peak demand
  - 10-Minute reserve (5-7.5% spinning reserves)
  - 30-Minute reserves (5-7.5% non-spinning reserves)
  - Consider additional margin depending on historic RE forecast error

Cost of providing reserves due to RE



Costs 2017 € per MWh

VRE Penetration (% of annual Energy)

Impact on Thermal Generation

Thermal units, technical and financial impact

Existing thermal fleet is expected to experience:

- **Increased cycling**
  - Frequent start/stops
  - Higher maintenance cost

- **Increased ramping**
  - Frequent ramp up/down requirement
  - Higher maintenance cost

- Overall increase in maintenance costs for thermal units

Modifications to thermal fleet can enable faster cycling and ramp up/down

Thermal units, technical and financial impact

Existing thermal fleet is expected to provide:

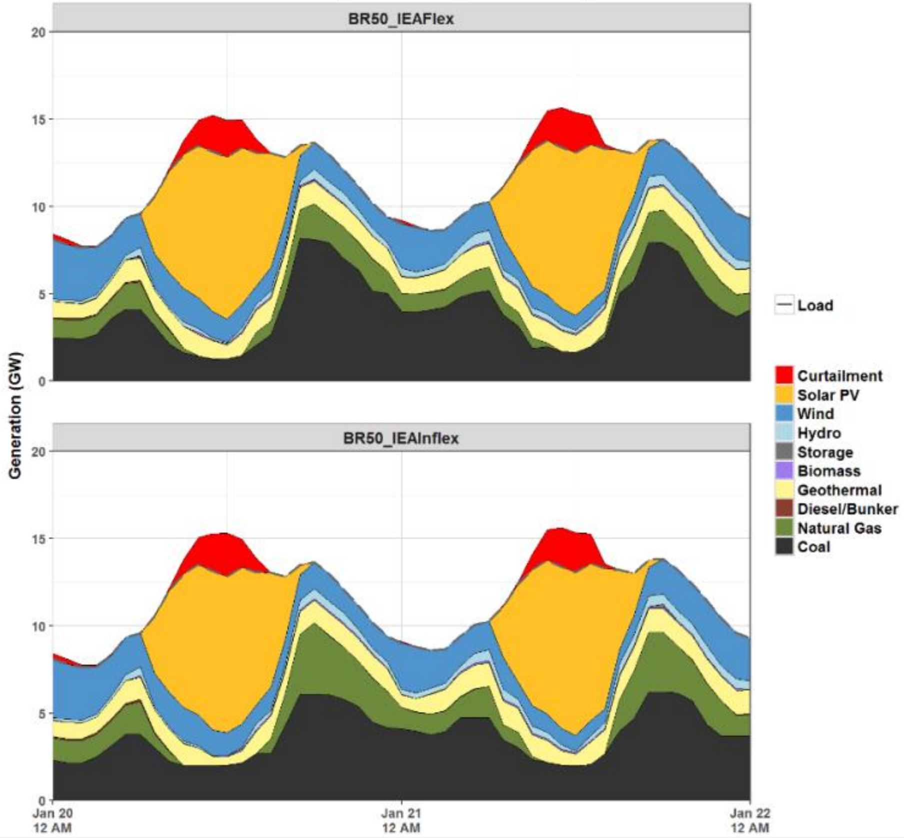
- Higher spinning reserve / part load operation / reduced technical minimum (To about 40% capacity)
  - Less efficient performance
  - Higher emissions, and
  - Higher cost of generation
- Lower plant load factor (PLF) due to higher RE generation
- Higher LCOE

Under-utilization of thermal fleet (loss of design life)

Case study: Philippines

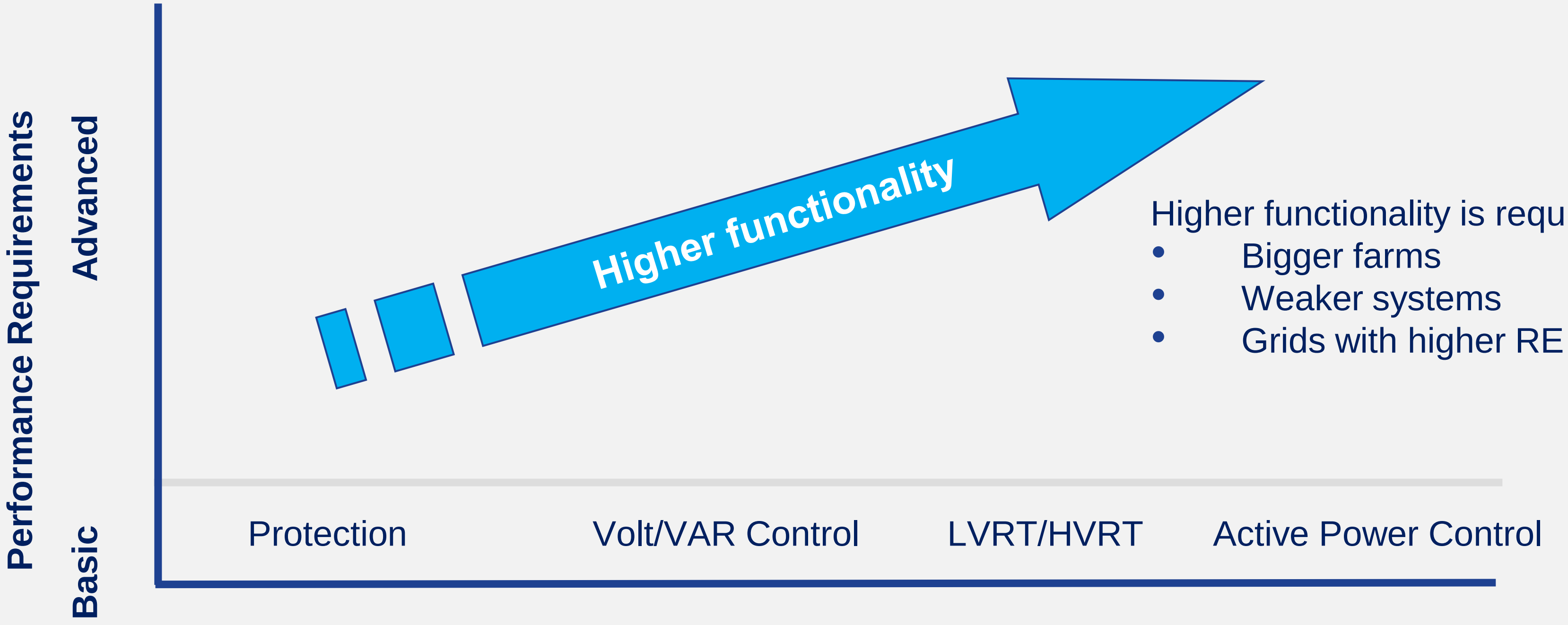
- Study to understand the implications of higher amounts of RE (30% or 50%) in the Luzon-Visayas grid in 2030?
- Study sensitivity to conventional generator flexibility:
    - More flexible: Lower minimum level and shorter minimum downtime
    - Less flexible: Higher minimum level and longer minimum downtime
- It was concluded that more flexible thermal generation resulted in:
    - Higher annual wind and solar penetration
    - Lower curtailment, and
    - Lower variable costs

Figure. More flexible thermal plants (top) vs. less flexible thermal plants (bottom)



RE Interconnection Requirement

Interconnection requirement



Higher functionality is required for:

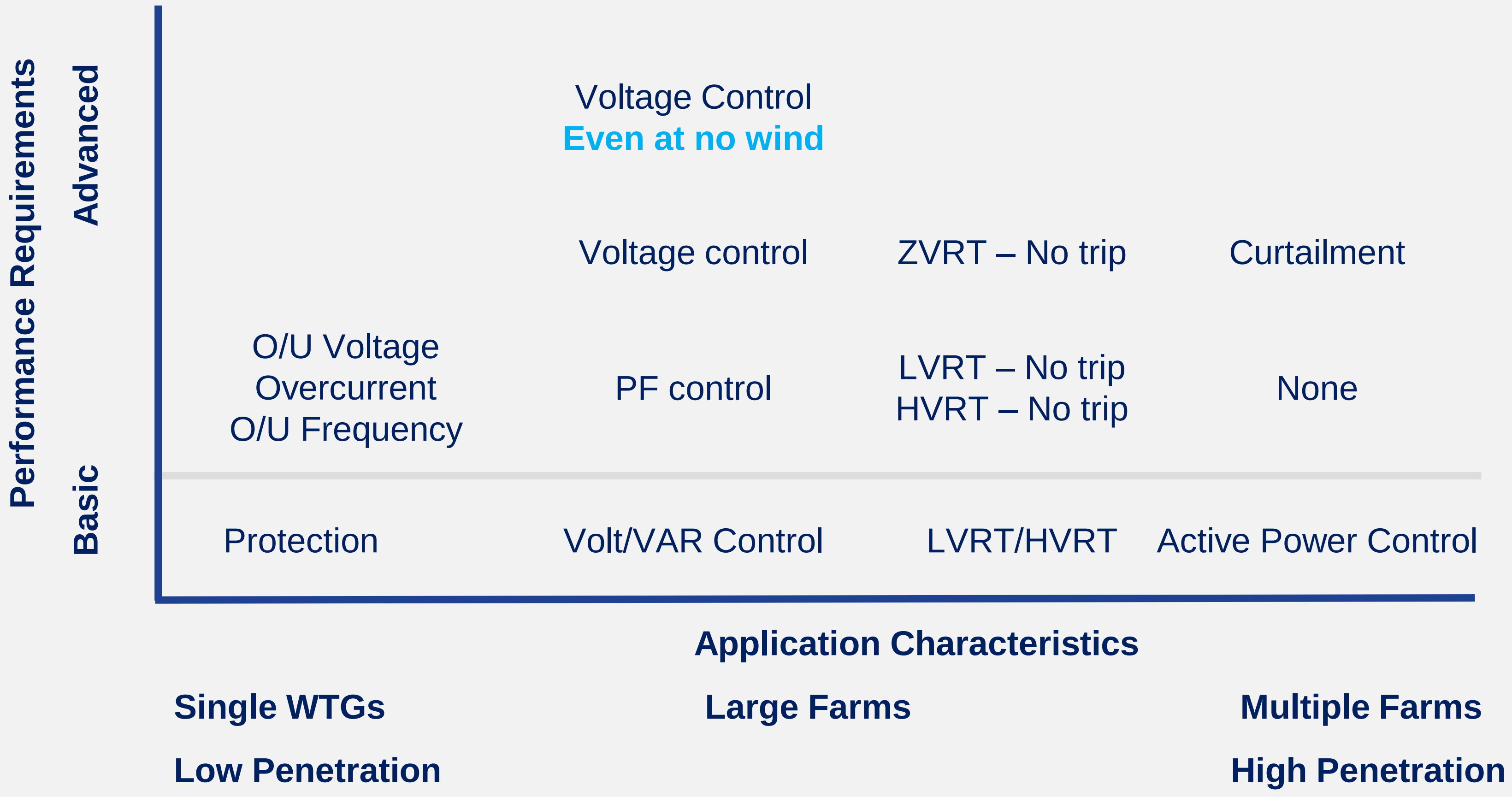
- Bigger farms
- Weaker systems
- Grids with higher RE penetration

Application Characteristics

Single WTGs **Large Farms** **Multiple Farms**

Low Penetration **High Penetration**

Interconnection requirement



Performance Requirements

Advanced

Basic

Voltage Control
Even at no wind

Voltage control

ZVRT – No trip

Curtailment

O/U Voltage
Overcurrent
O/U Frequency

PF control

LVRT – No trip
HVRT – No trip

None

Protection

Volt/VAR Control

LVRT/HVRT

Active Power Control

Application Characteristics

Single WTGs

Low Penetration

Large Farms

Multiple Farms

High Penetration

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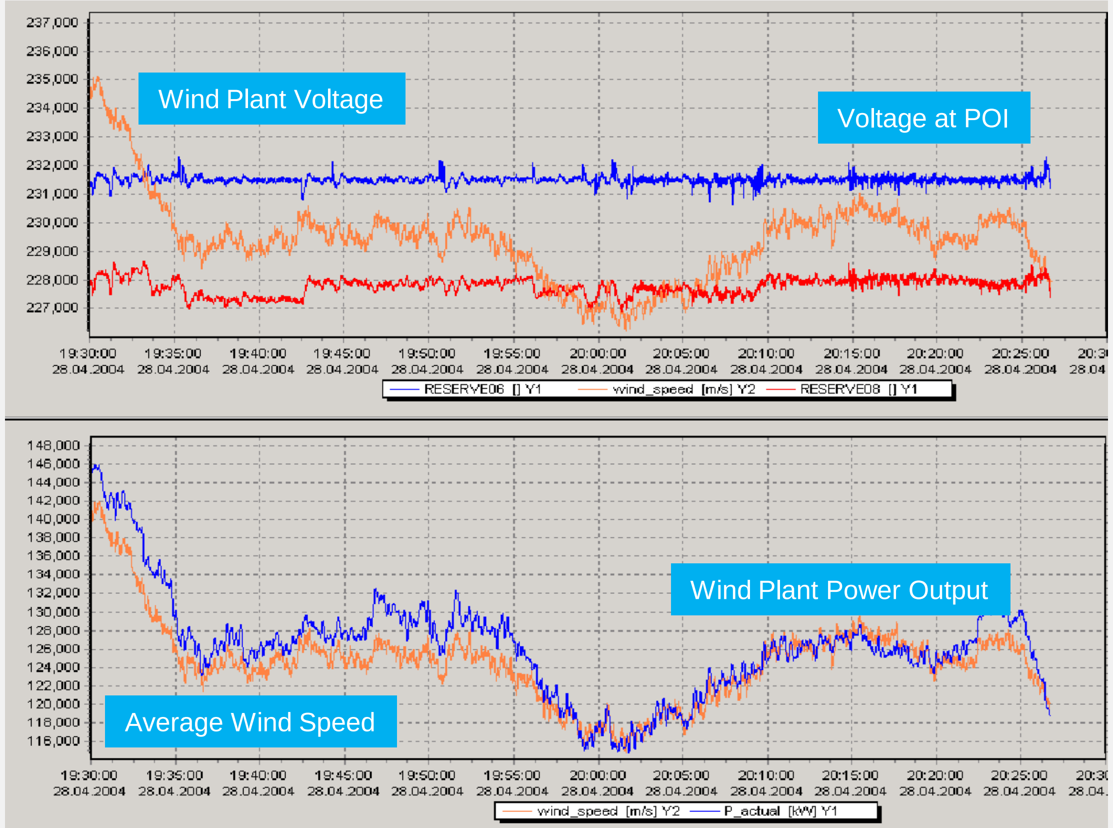
Grid-Friendly Features for Wind Turbine Generators (WTG)

Voltage control

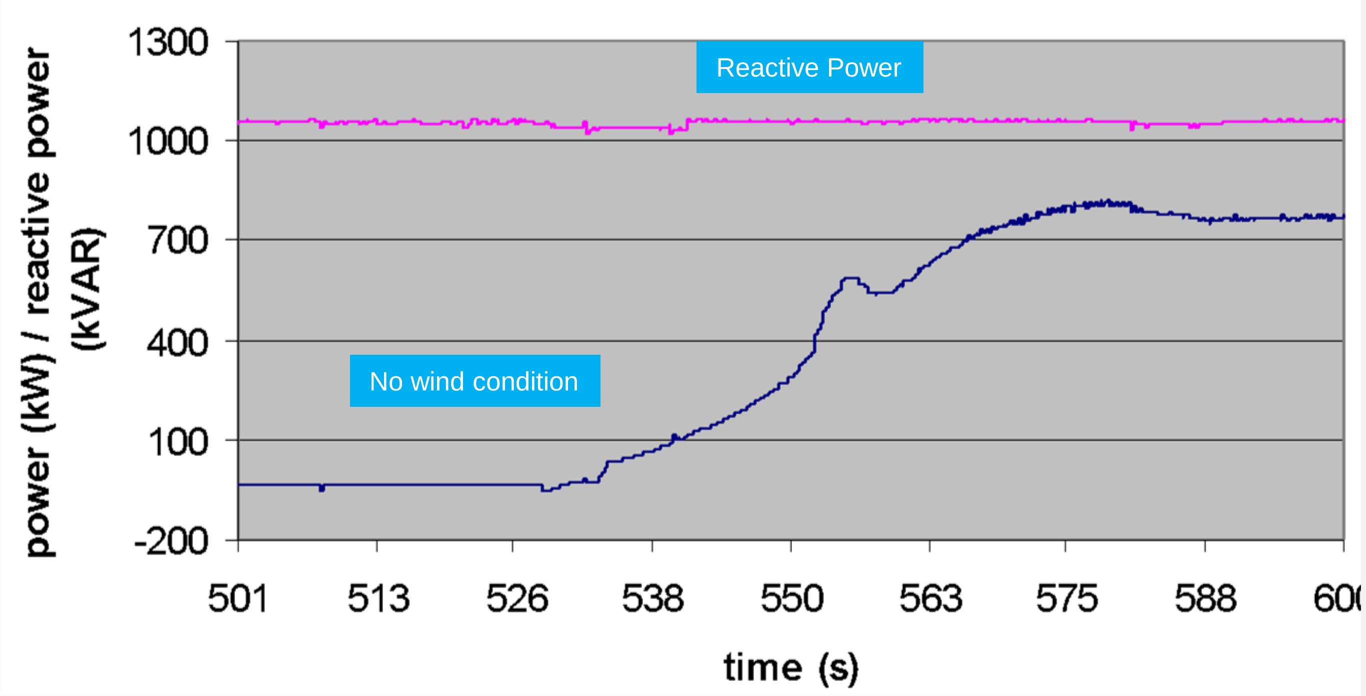
- Regulates grid voltage at point of interconnection
- Minimizes grid voltage fluctuations even under varying wind conditions
- Regulates total wind plant reactive power through control of individual turbine



Should maintain steady voltage at the point of interconnection (POI)

Reactive power control

- Remains on-line and feeds reactive power during system disturbances
- Feeds reactive power even at No-Wind condition
- Major grid performance and reliability benefits especially in weak grids and systems with high-wind penetration

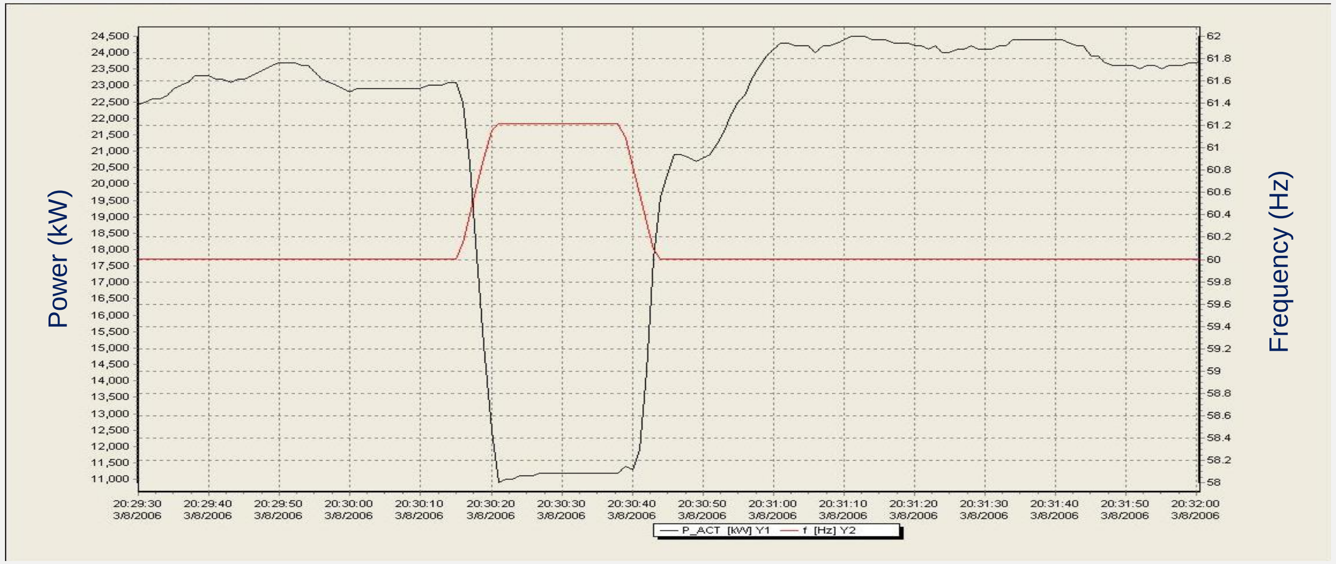


Should perform like STATCOM

Active power control

- Provides governor droop response, regulates system frequency and does not require reducing normal plant output
- Regulates/Limits the rate of change in power under varying wind conditions
- Manages Power Ramp rates with Startup/Shutdown turbine sequencer

2% Frequency Increase

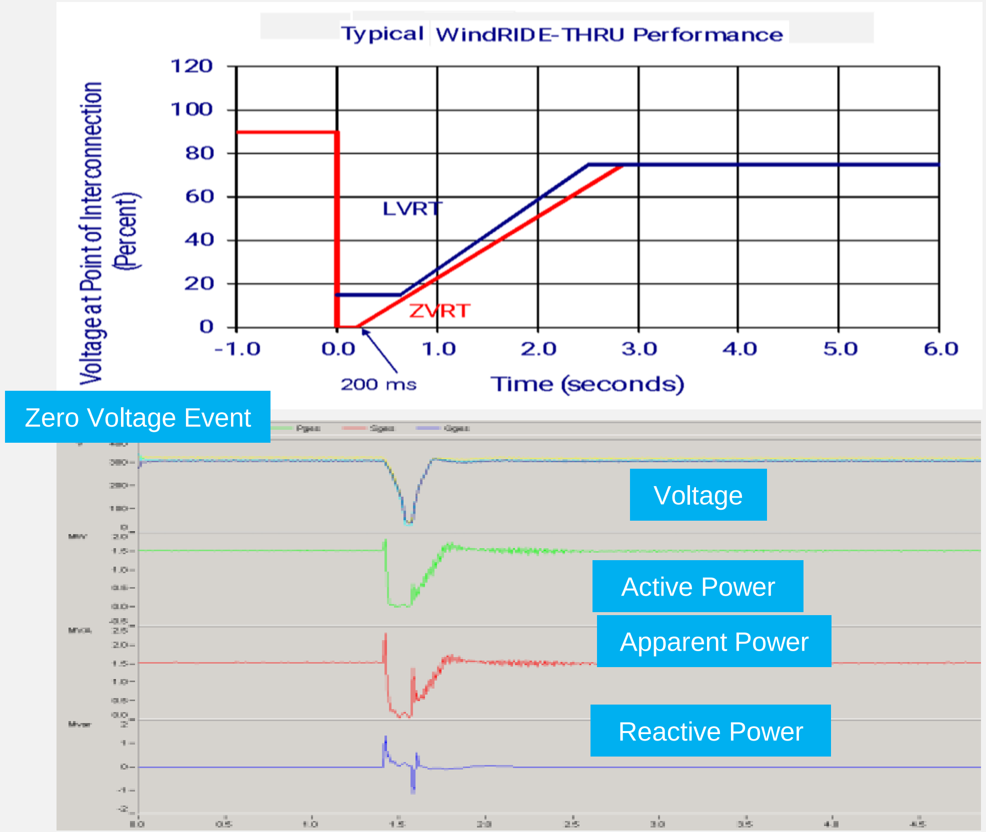


50% Power Reduction

Pitch control is used to achieve droop control

Fault ride-through capability

- Remains on-line and feeds reactive power during system disturbances
- Meets grid requirement with Low/Zero Voltage Ride-Through (LVRT/ZVRT) Capability
- Meets transmission reliability standards similar to thermal generators



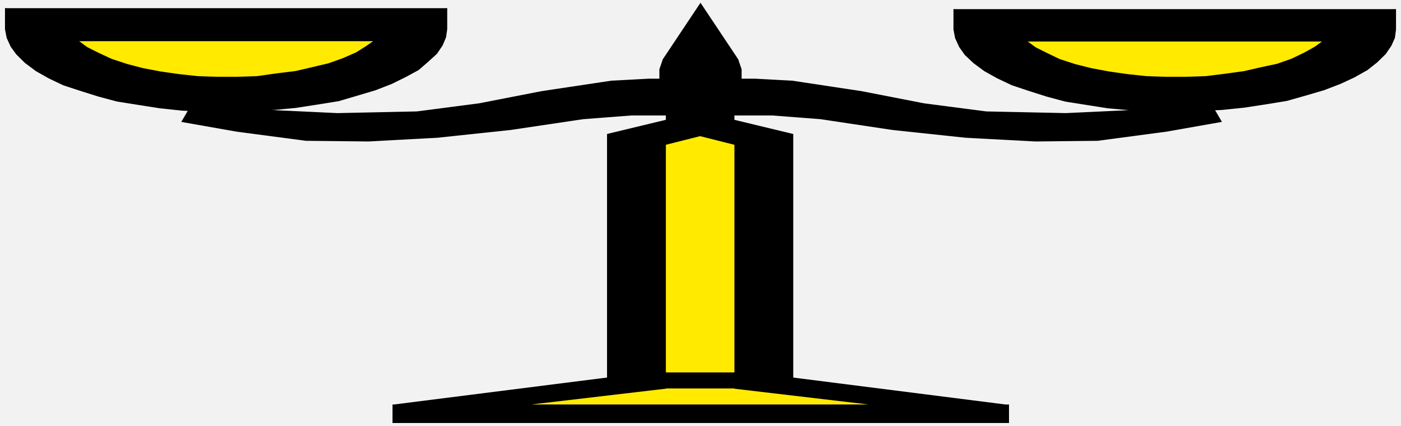
Should perform like synchronous generator at POI

Dynamic response

- Inertial response similar to conventional synchronous generators for large under-frequency grid events
- A temporary 5-10% increase in power
- Duration of order of several seconds
- For under-frequency greater than 0.5 Hz
- Introduced as wind turbines curtailing (limit) power production to allow margin for an increase in power output

Participate in grid dynamics to maintain stability

WTG technical standards and grid codes



Tight
Over-designed and
more expensive equipment

Loose
Compromised system reliability and
stability

Grid Code Functional Specifications

Grid performance holds the key

Grid-Friendly Features for Solar

Solar grid-following inverters

- Synchronize their output with the grid voltage and frequency.
- Current sources that track the grid angle and magnitude to inject or absorb active and reactive power.
- Depend on the grid to provide a stable voltage and frequency reference.

Limitations

- They cannot operate in islanded or off-grid mode, which limits their flexibility and resilience.
- They cannot provide voltage and frequency support to the grid, especially during disturbances or outages.
- They cannot provide ancillary services to the grid, such as inertia, system strength, voltage regulation, and frequency response.
- They may cause stability and security issues for the grid, especially when there is a high penetration of renewable energy sources.

Applications

- Grid following is widely used for many grid-connected applications with lower solar penetration.

Solar grid-forming inverters

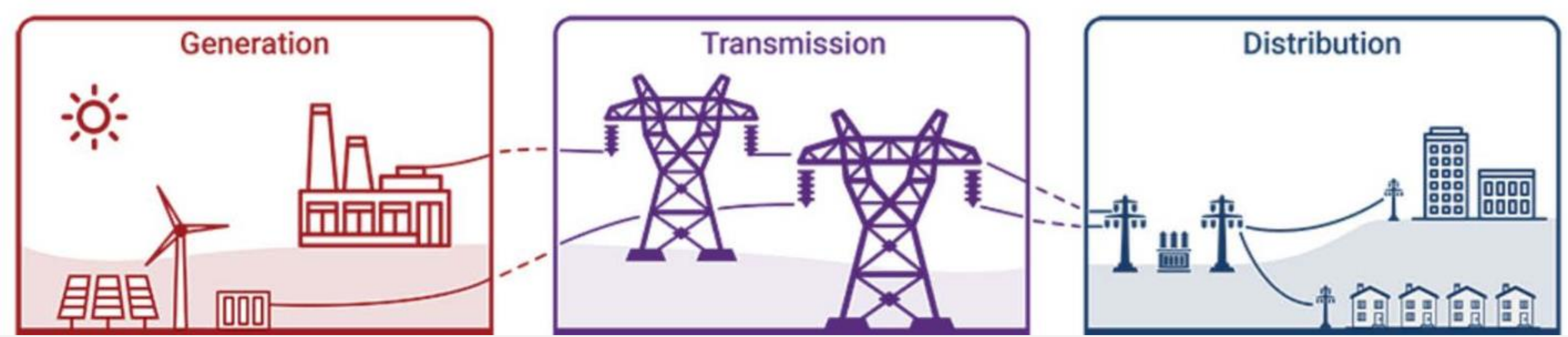
- Grid-forming inverters can adjust their output power and voltage in response to grid conditions and coordinate with other sources to balance supply and demand.
- They can provide droop control or hierarchical control.
- They can provide various ancillary services to the grid, such as inertia, system strength, voltage regulation, and frequency response especially during disturbances or outages.
- They can help restore the grid after a blackout, by creating a stable voltage and frequency reference for other sources to synchronize with.
- They can adjust the modulated voltage at POI vis-a-vis grid voltage.
- They act like synchronous generators, that maintain grid stability and reliability.

Applications

- Grid forming is a key technology for integrating higher RE into the grid ensuring reliability and stability.

Role of Battery Energy Storage System (BESS)

Role of BESS



- Address supply disruptions
- Address variability of RE sources
- Provide peaking capacity

Integration Economics

RE benefits

Country		Bangladesh			Sri Lanka	
Project		**1,000 MW Wind**	**1,000 MW Solar**	**1,000 MW Hydro**	**1,000 MW Wind**	**1,000 MW Solar**
Reduction in Thermal Generation		7.0%	2.0%	7.0%	7.0%	1.4%
Reduction in Production Cost		9.5%	3.9%	15.0%	29.0%	18.0%
Reduction in Emission		5.5%	2.5%	10.0%	21.0%	6.3%
Fuel Displaced	**Oil**	12.0%	5.5%	20.0%	-	-
	Gas	-	-	-	47.0%	-
	Coal	-	-	-	12.0%	33.0%

Source: Joshi et al. (2020)

Integration costs

- Typically, three components are included under integration costs:
    1. **Costs (or benefits) from interaction with other power plants:** Most significantly, the increase in the specific costs of production of other power plants due to the reduction of their full load hours.
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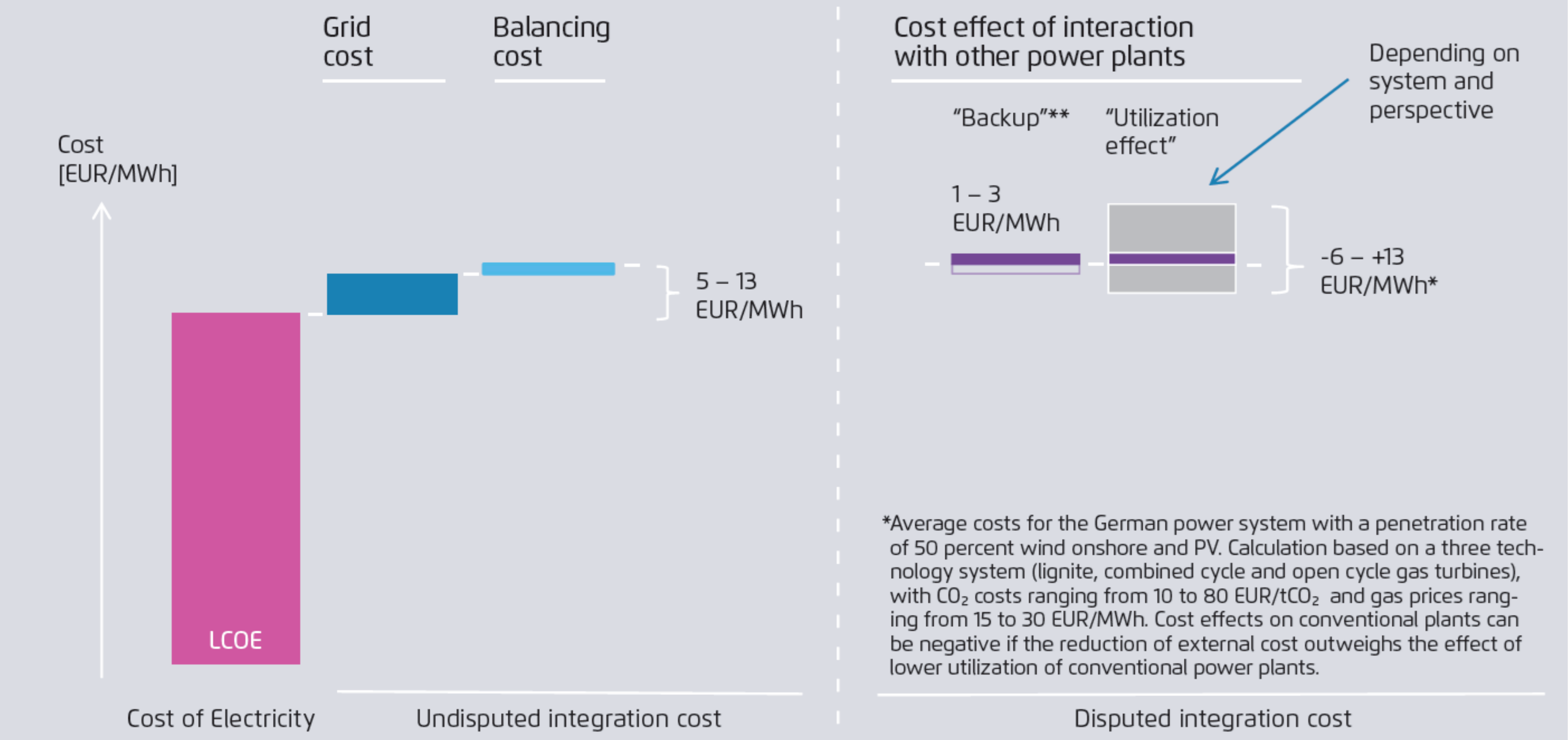
    3. **Balancing Costs:** Costs to offset differences between forecasts and actual production.
- Each of these costs occurs when a new power plant is added to an existing power system – be it wind, solar or thermal.
- Due to their specific, weather-dependent generation profile, integration costs for wind turbines and solar PV differ from those of base load plants in several aspects.

Overview of “integration costs” components



*Average costs for the German power system with a penetration rate of 50 percent wind onshore and PV. Calculation based on a three technology system (lignite, combined cycle and open cycle gas turbines), with CO_2 costs ranging from 10 to 80 EUR/tCO_2 and gas prices ranging from 15 to 30 EUR/MWh. Cost effects on conventional plants can be negative if the reduction of external cost outweighs the effect of lower utilization of conventional power plants.

- Grids and balancing costs are well defined and are rather low. These costs are between +5 to +13 EUR/MWh, even with high shares of RE.

- “Utilization effect” is difficult to quantify and new plants always modify the utilization rate of existing plants. These costs are between -6 and +13 EUR/MWh.

Source: Agora Energiewende, 2015

UKERC view - Cost of RE on the system

1. **Raising reserve requirements**
    - Grid operators already need to hold flexible generators in reserve, in case conventional power stations break down without warning.
    - Short-term fluctuations in the output of wind and solar can mean more reserve is needed.
    - The UKERC review says this could add up to **£5/MWh**, if wind and solar supply reaches **30%** of electricity demand.
2. **Peak demand management**
    - The second category of costs is maintaining enough capacity to meet peak demand at all times.
    - This depends on the reliability targets that drive the spinning reserve margin.
    - It is a function of LOLE (Loss of Load Expectation).

UKERC view - Cost of RE on the system

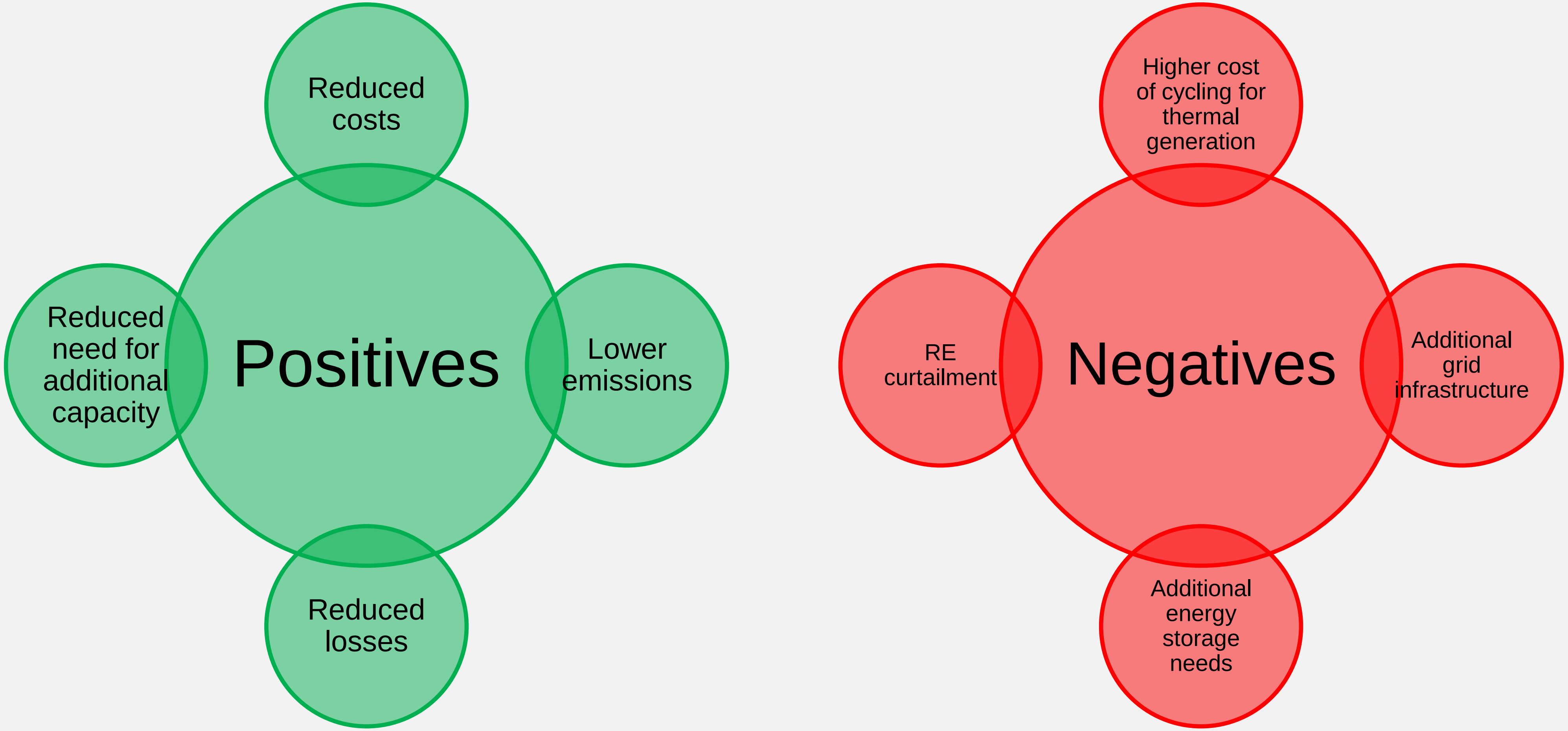
3. **Strengthen transmission network**
    - The grid already needs a rolling program of renewal and expansion.
    - As solar and wind expand, the additional cost could be **£5-20/MWh** and, again, the top end relates to inflexible grids.
4. **Curtailment**
    - Wind farm output may be wasted because there is not enough grid capacity to get the power to customers.
    - Curtailment is “generally very low”.
    - Investments in electricity grids can reduce it further, while raising network costs.
    - The system **costs can overlap or trade off** against each other.

UKERC view - Cost of RE on the system

5. **Inefficient operation of thermal fleet**
    - The efficiency of conventional power stations, can be impaired if they have to turn on and off in response to variable renewable generation instead of operating steadily.
    - Majority of studies finds this impact to be **“very small”**.
6. **Reducing system inertia**
    - The increase in renewables and reduction in fossil fuel plant changes the resilience of the electricity system by reducing a quality called **inertia**.
    - Inertia traditionally stems from the spinning mass of steam-driven turbines.
    - Costly changes in system inertia are only likely to become significant when wind and solar pass **50% grid penetration**.

Concept of system value (SV)

SV is the overall benefit from addition of wind or solar power source to the power system



Cost of electricity (CoE) Vs. system value (SV)

- Achieving power system transformation requires a shift in the economic assessment of VRE.
- The traditional focus on the levelized cost of electricity (LCOE) is no longer sufficient.
- If SV > CoE, additional VRE capacity will help to reduce the total cost of the power system.
- As the share of VRE generation increases, the variability of VRE generation and other adverse effects can lead to a drop in SV.

Summary

- Higher RE generation regime desires thermal plants to be more flexible during base load and mid-merit operation.
  - Increased number of start/stops, Faster ramp up/down performance, Part-load operation
- Higher RE penetration would have significant cost impact depending on energy mix:
  - Higher CAPEX for RE capacity additions
  - Higher maintenance costs for thermal plants due to flexible operation
  - Higher cost of energy (COE) due to part load operation
  - Additional CAPEX for grid code compliance at the POI and for grid friendly features of RE technologies
- Overall operational cost depends on generation mix, technical standards, grid codes, LOLE targets, emissions targets, REC certificates, etc.
- SV is a better indicator as compared to LCOE.

Questions?

Economic and Social Commission for Western Asia

Integration Costs of Wind and Solar Power

Impact of RE on Transmission Systems

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Shared Prosperity **Dignified Life**

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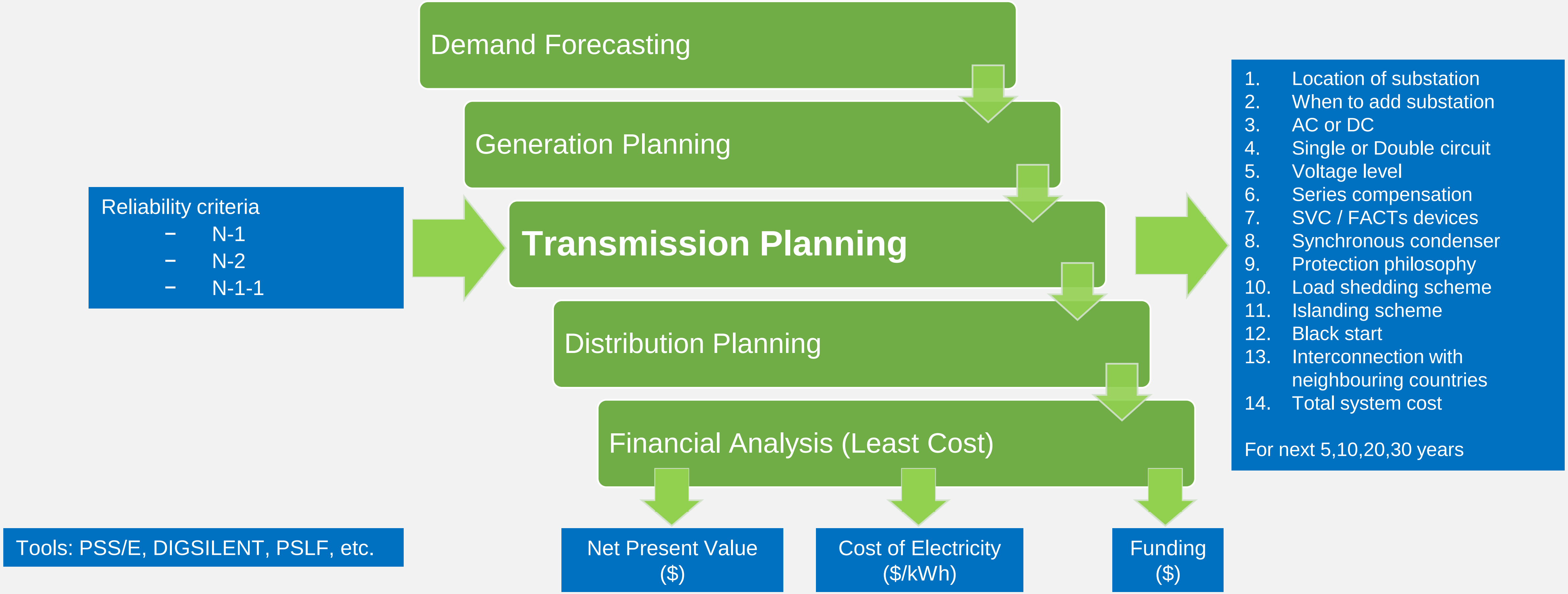
Impact on Transmission Planning

Transmission planning



Demand Forecasting

Generation Planning

Transmission Planning

Distribution Planning

Financial Analysis (Least Cost)

Reliability criteria
- N-1
- N-2
- N-1-1

1. Location of substation
2. When to add substation
3. AC or DC
4. Single or Double circuit
5. Voltage level
6. Series compensation
7. SVC / FACTs devices
8. Synchronous condenser
9. Protection philosophy
10. Load shedding scheme
11. Islanding scheme
12. Black start
13. Interconnection with neighbouring countries
14. Total system cost

For next 5,10,20,30 years

Net Present Value ($)

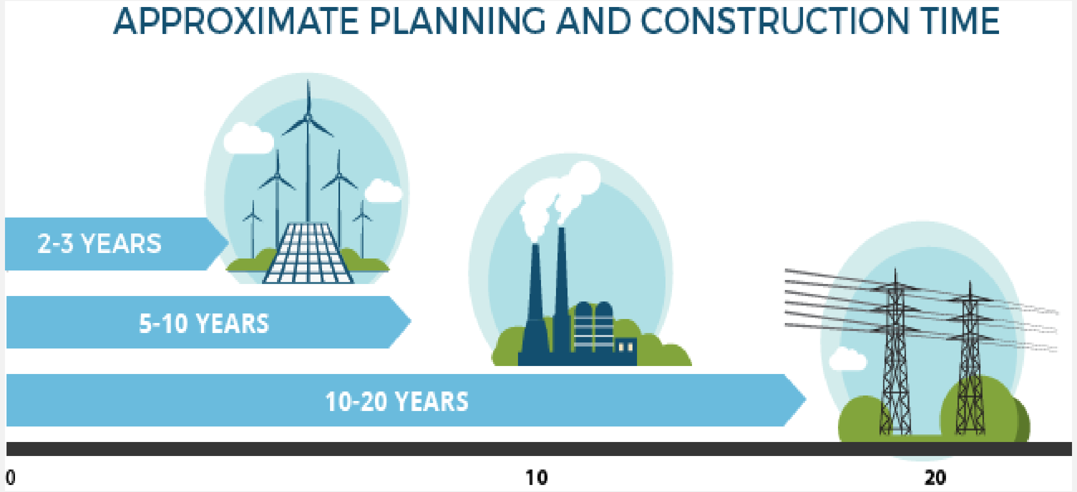
Cost of Electricity ($/kWh)

Funding ($)

Tools: PSS/E, DIGSILENT, PSLF, etc.

Transmission lines vs. RE site development

- RE-rich resource locations are:
  - Often far away from load centers
  - Commercially attractive for developers
  - Can be developed within 2-3 years
- Transmission networks to RE-rich resource locations:
  - Require new build
  - Limited access due to tough terrains
  - May require 5-10 years to plan and build

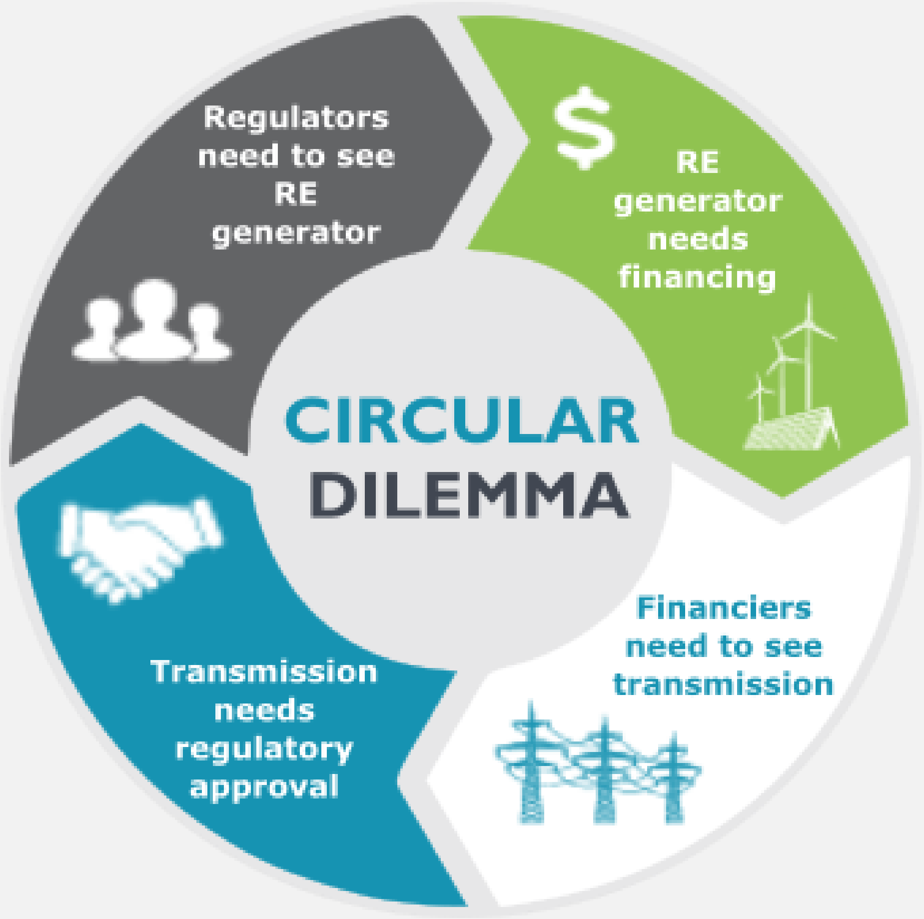


Circular dilemma

- The timescale misalignment leads to a common circular dilemma in generation and transmission planning.

- Financing for remote generation projects is not available without transmission access, but transmission lines cannot be built without a demonstrated need for service and certainty for cost recovery.

- Renewable energy planning that does not consider transmission expansion may force power systems to connect to less important loads.

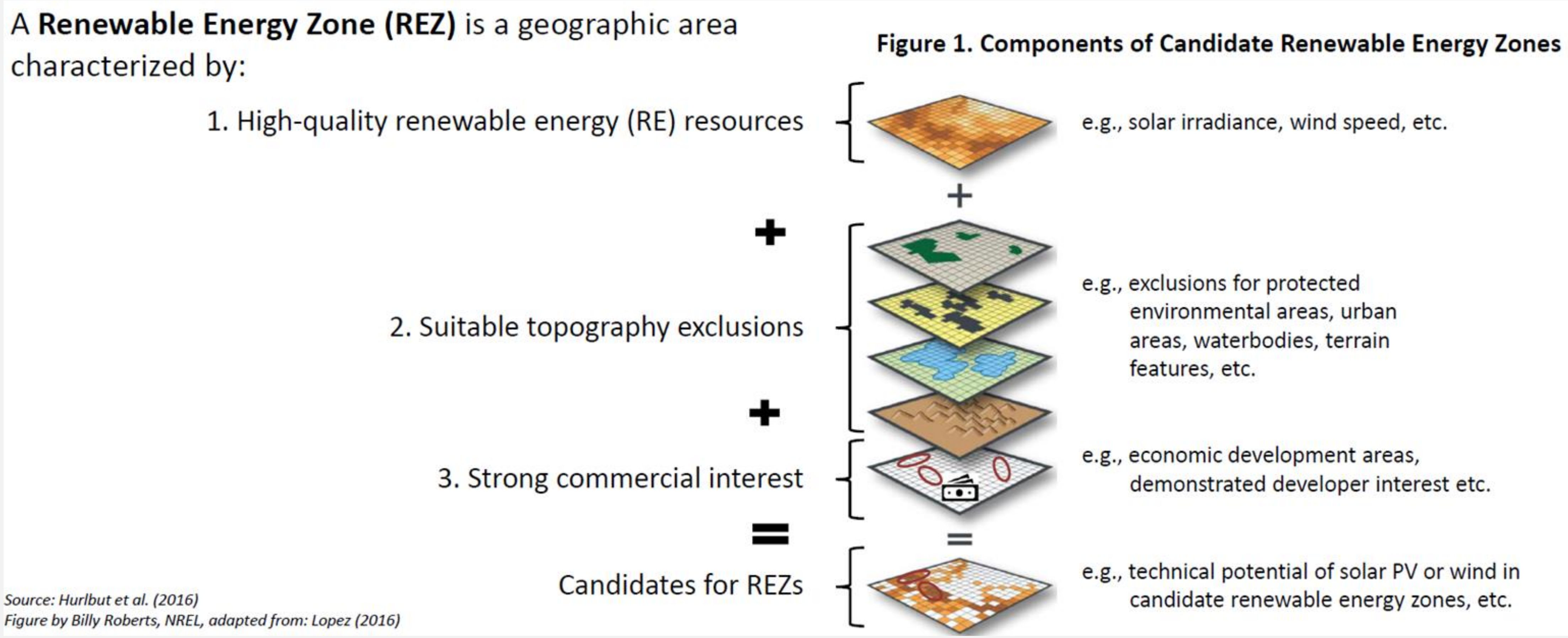


Current industry practice

- Upgrade the existing transmission network to overcome challenges of scaling up renewable energy generation in power systems in the short term.
- Identify and develop dedicated GREEN corridors to connect potential RE rich sites for development in future.
- Plan and develop cross border networks for power trade, as lots of energy (mainly RE) is expected to be available.
- Install VAR resources at optimal locations to address the voltage issues arising due to high RE.
- Develop appropriate transmission networks (AC or HVDC) depending on network requirements.

Renewable Energy Zone (REZ)

Renewable energy zones (REZ)



A **Renewable Energy Zone (REZ)** is a geographic area characterized by:

1. High-quality renewable energy (RE) resources

+

2. Suitable topography exclusions

+

3. Strong commercial interest

=

Candidates for REZs

Figure 1. Components of Candidate Renewable Energy Zones

e.g., solar irradiance, wind speed, etc.

+

e.g., exclusions for protected environmental areas, urban areas, waterbodies, terrain features, etc.

e.g., economic development areas, demonstrated developer interest etc.

=

e.g., technical potential of solar PV or wind in candidate renewable energy zones, etc.

Source: Hurlbut et al. (2016)
Figure by Billy Roberts, NREL, adapted from: Lopez (2016)

Renewable energy zones (REZ)

REZ concept allows for the timely development of integrated generation and transmission. As an example, the REZ process:

- Assesses the highest-quality RE resources that can be feasibly developed.
- Ensures that REZs have a high probability of development (expressed commercial interest).
- Studies transmission expansion options to connect REZs to load.
- Ensures that transmission plans comply with regulatory review criteria that may include reliability standards, renewable energy goals, and/or environmental goals.
- Results in transmission plan implementation that details how REZs will be connected along the planning horizon allowing developers to coordinate expansion of RE generation in these zones.

Larger Balancing Area

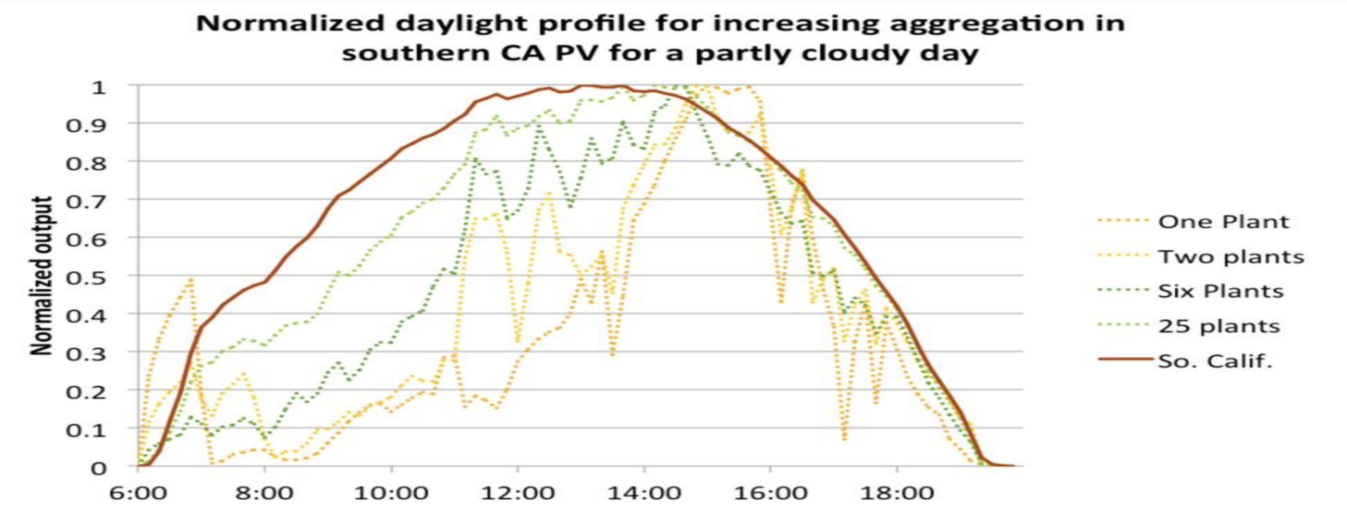
Larger balancing area

Why bigger balancing areas are helpful?

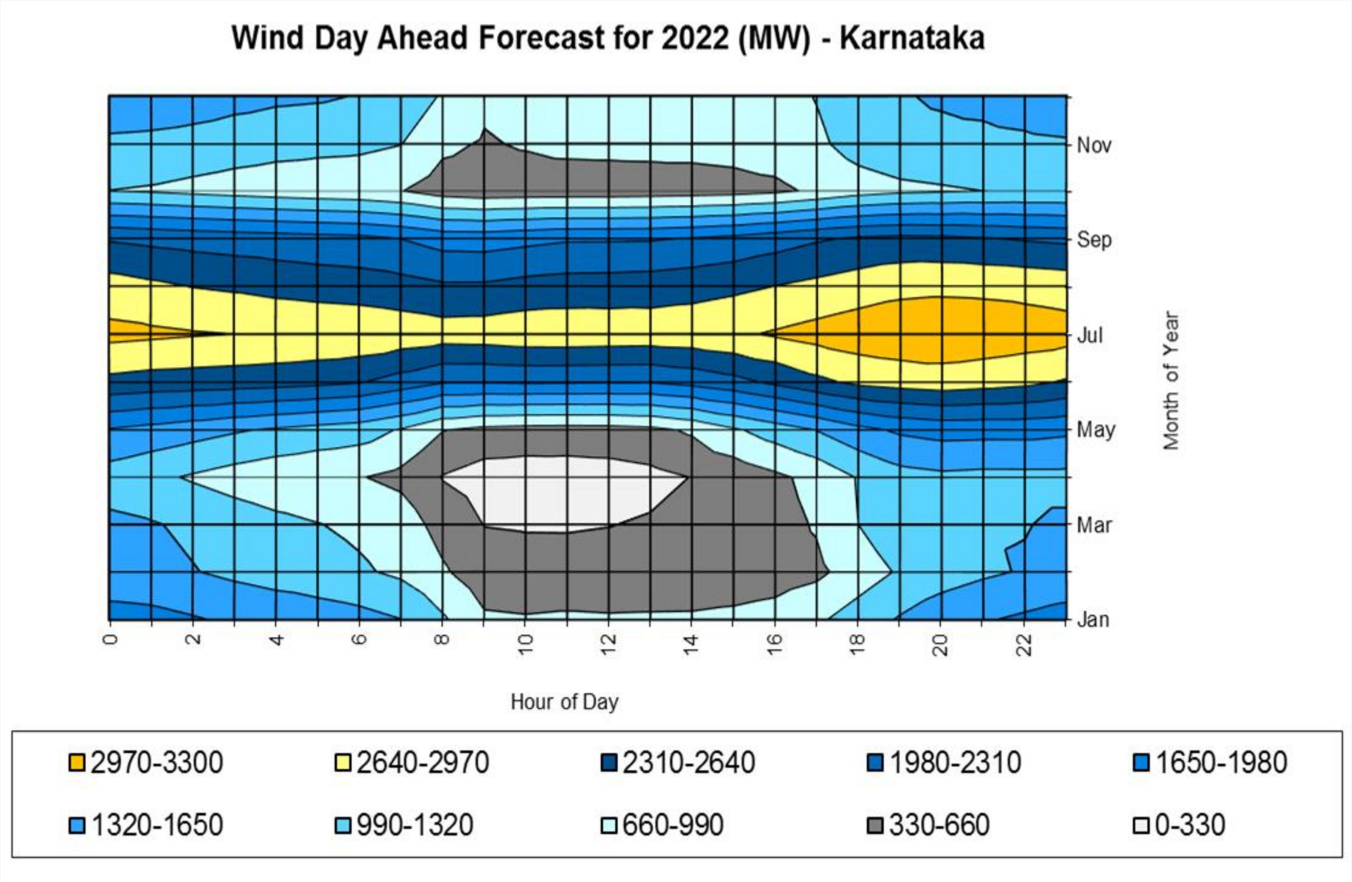
- Wind and solar resources smooth out with geographic diversity.
- Solar generation reaches its maximum value during the day when wind generation is typically low. Seasonally, wind generation is highest during monsoon months when solar generation is low.
- Load smooths out.
- More dispatchable generators to manage variability and uncertainty.

Examples

- MISO is 125 GW system with relatively few impacts of wind on system balancing.
- Portugal had 24% wind energy penetration in 2014 with instantaneous hourly wind penetration hitting 90%, but they did NOT need to curtail wind, due to Spain.



2022 wind estimate in Karnataka, India



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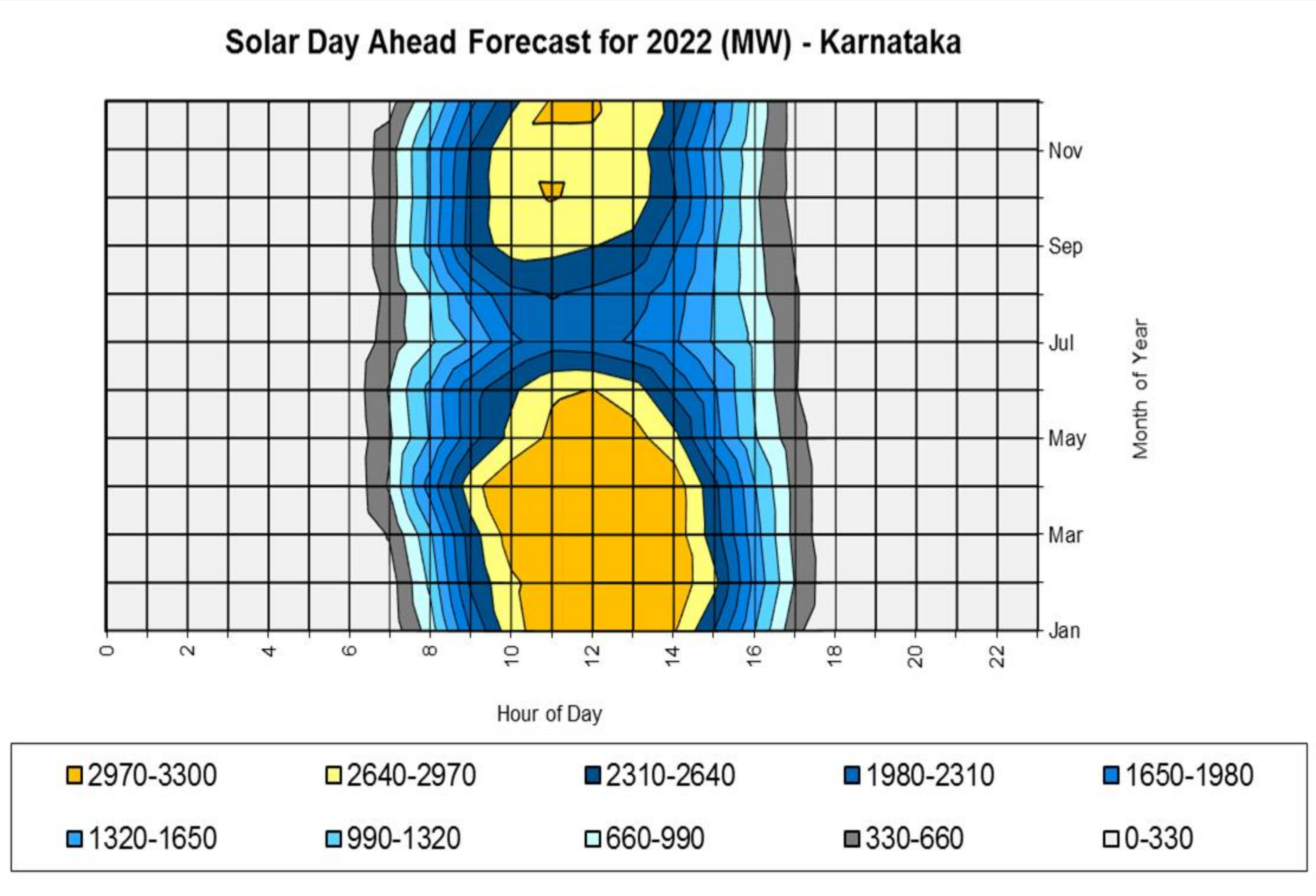
2022 solar estimate in Karnataka, India



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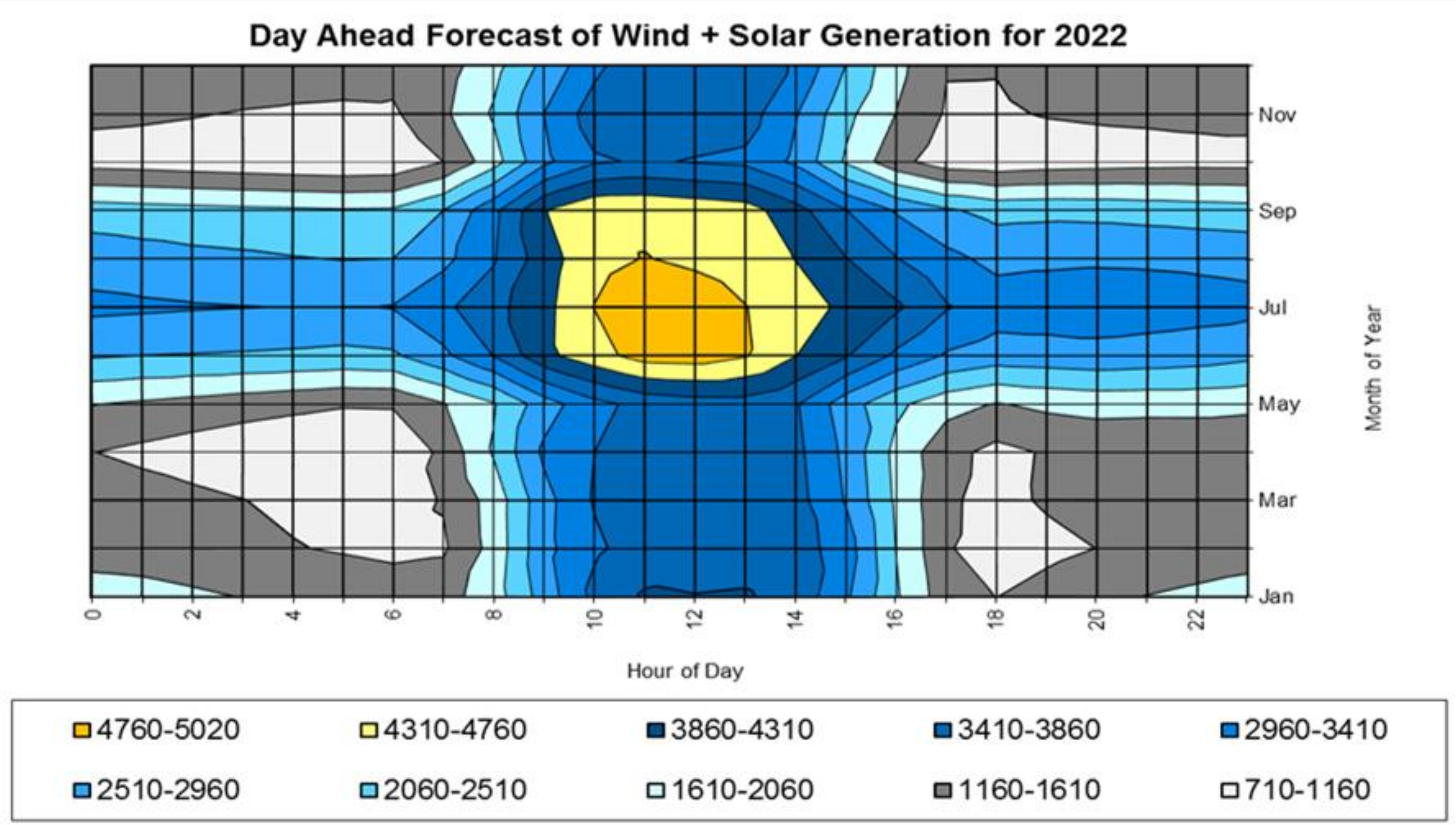
2022 wind + solar estimate in Karnataka, India



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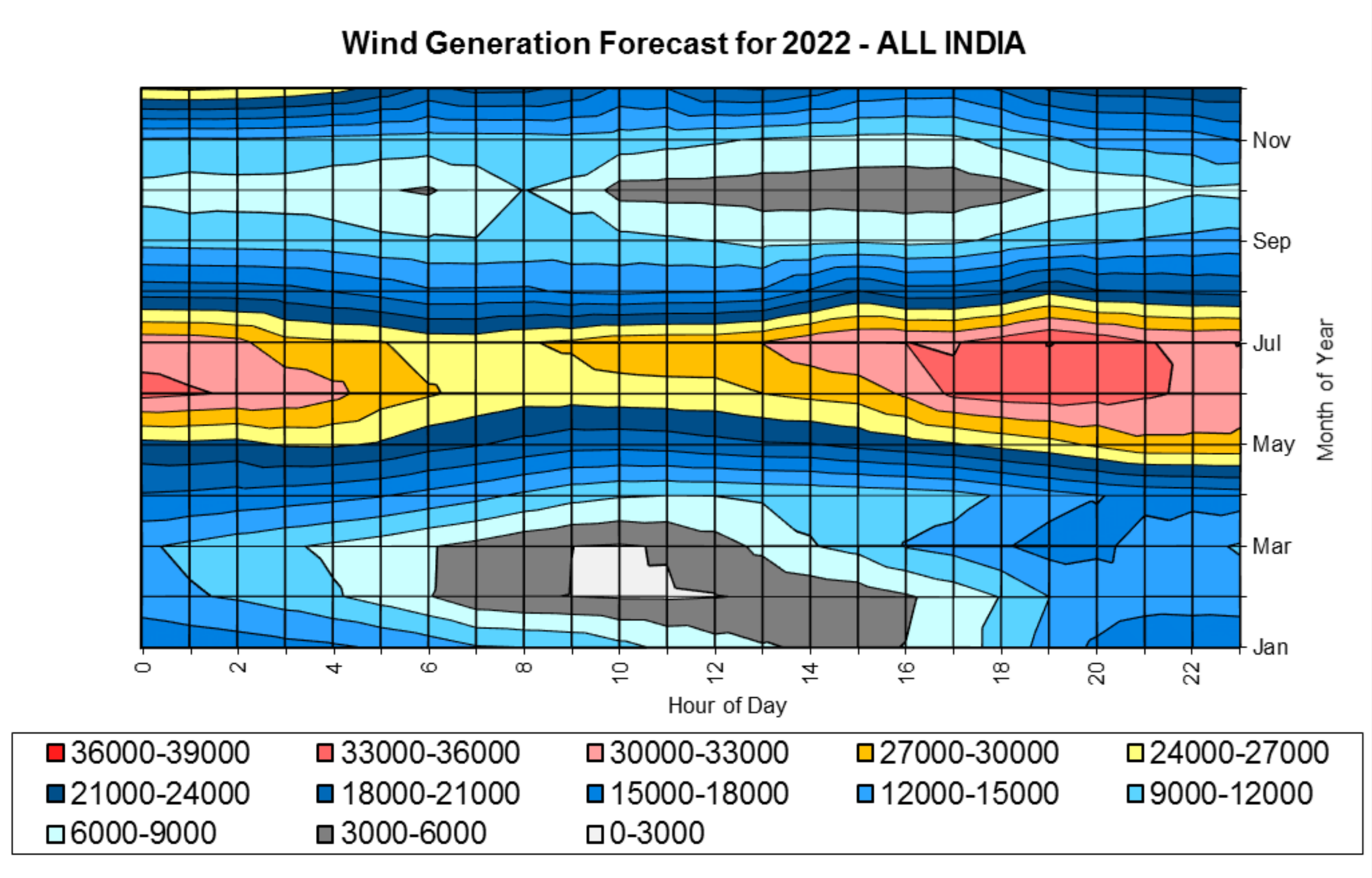
2022 wind estimate in India (60 GW)



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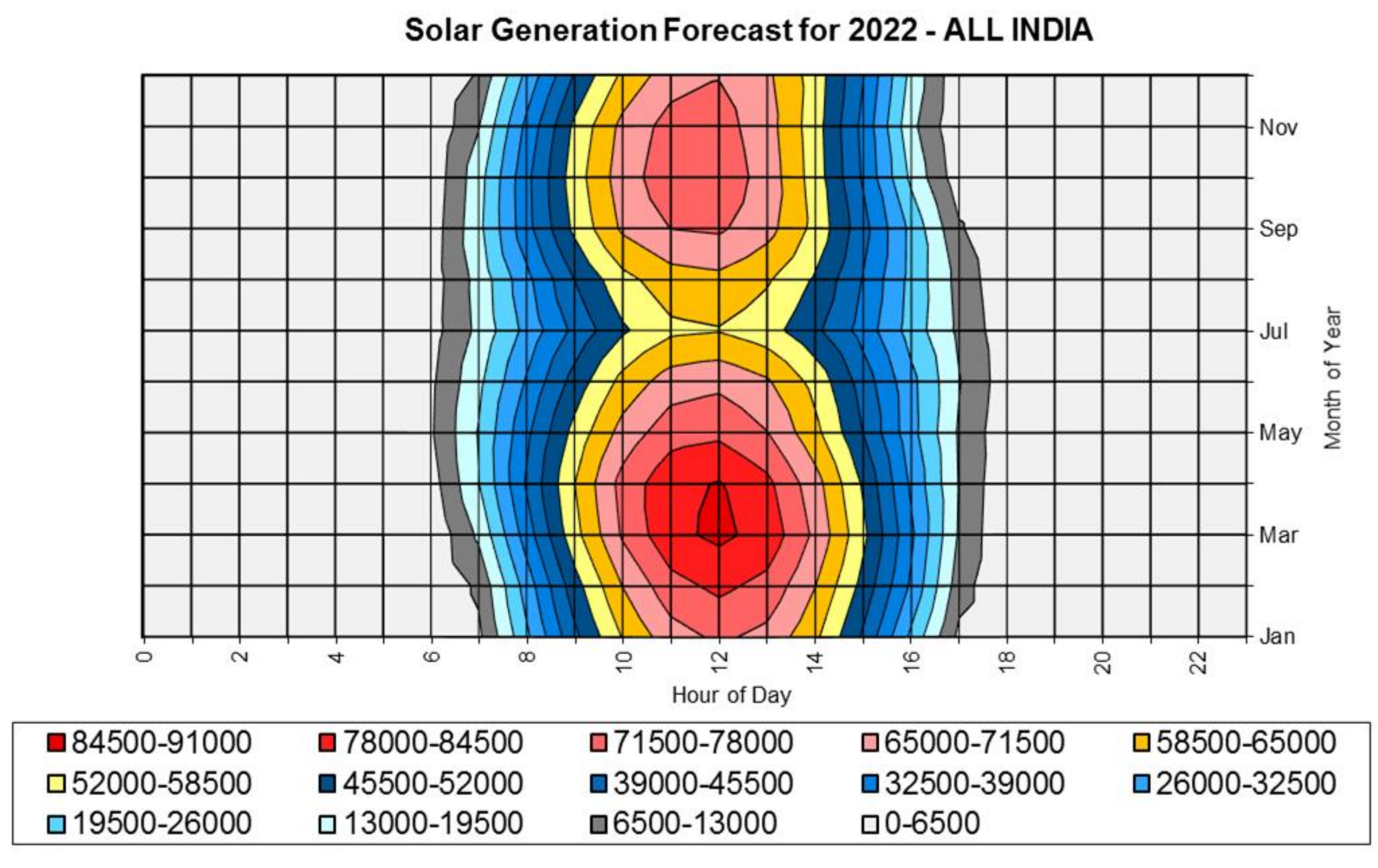
2022 solar estimate in India (100 GW)



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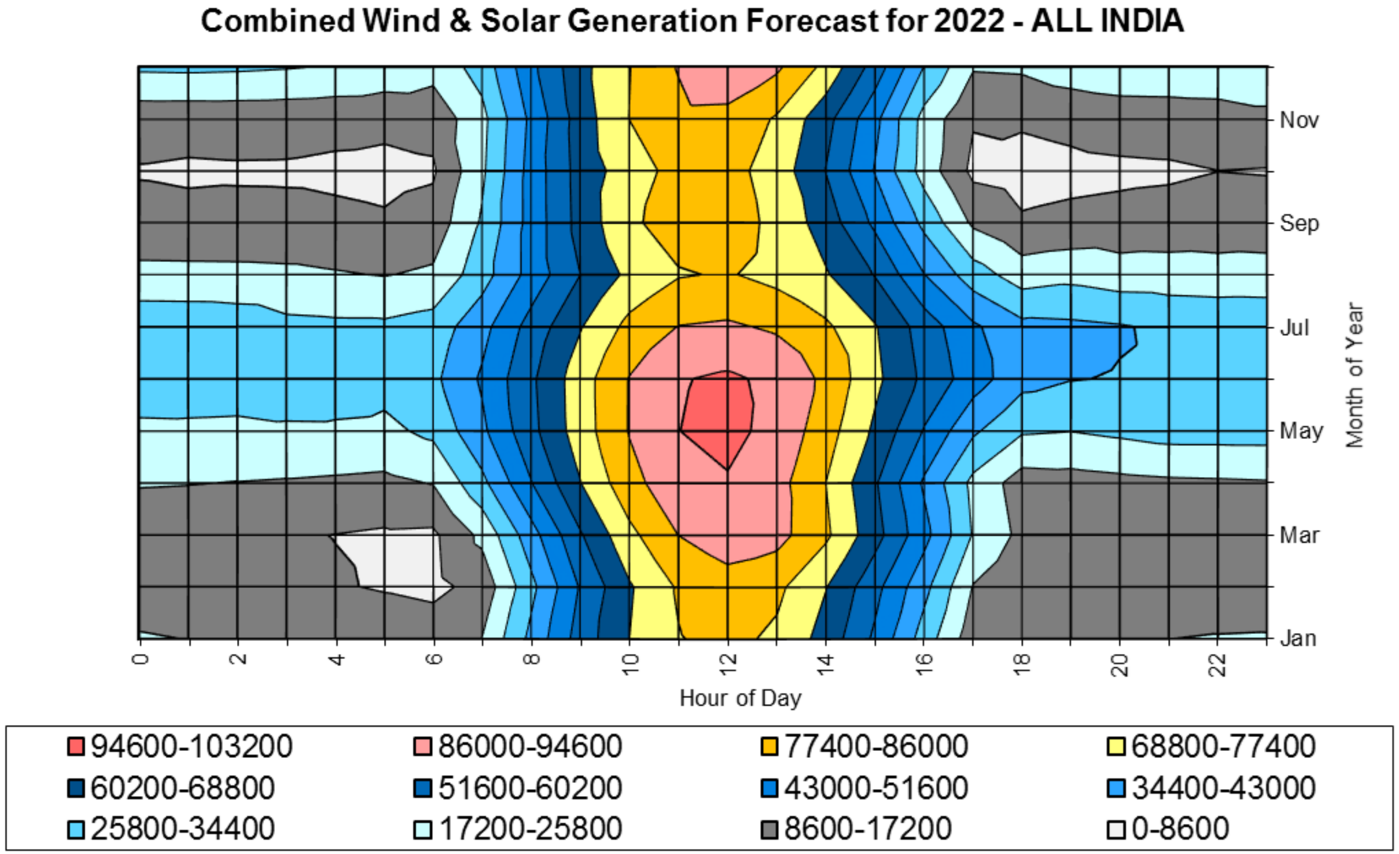
2022 wind + solar estimate in India (160 GW)



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Cross border energy trade

- Power trade can expand the geographic diversity of the balancing area to support RE via:
  - Larger pool of resources
  - More diverse set of generation characteristics
  - Seasonal and diurnal optimization of power provision
  - Access to clean but non-native resources (wind, hydro, land, etc.)
  - Access to low-cost generation option

Regional-level study requirement

- Regional interconnection study should assess the impact of a proposed interconnection between the interconnecting countries on overall grid performance.
- Some questions that such a study can answer:
  - How does the interconnection benefit in the short, medium, and long term?
  - How does the interconnection impact the reliability, resource adequacy, and resilience of the grid?
  - What challenges does an interconnection pose, and how to overcome these challenges?
  - What is the readiness level for an AC/HVDC interconnection?
  - What should be a master plan and a road map for development of cross-border interconnection?

Managing System Inertia and Voltage

Voltage and inertia support

- Due to high RE, the system experiences wide voltage variations.
- High RE also results in declining system inertia.
- It increases the rate of change of frequency in the system.
- Voltage control and inertia response come at an added cost.
    - Reduced inertia, assuming renewables do not have inertial emulation
    - Decreased primary control (governors), assuming renewables do not have primary controllers
- Voltage response can be managed through SVC, STATCOM, etc.
- Inertial response requires strong mass in the system.
- Synchronous condensers are widely used to provide both these support.

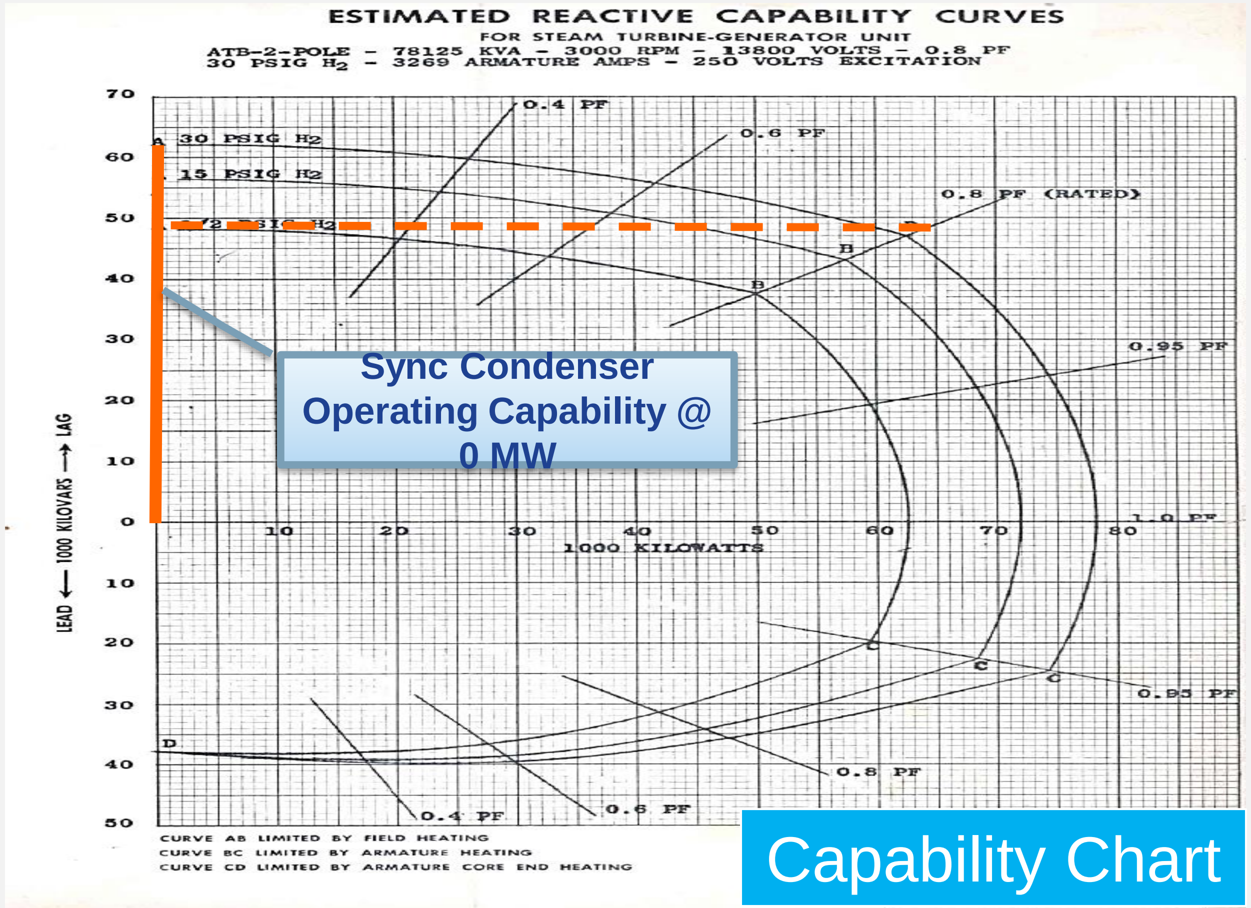
Synchronous condenser

- Generator to produce only reactive power (VARs)

- Over-excited VARs
  - Typically 30% or more over generator full-load operation
  - Further increases with new or rewound rotors

- Under-excited VARs
  - ~ Same as 0.95 leading PF

Synchronous condenser



Sync Condenser Operating Capability @ 0 MW

Capability Chart

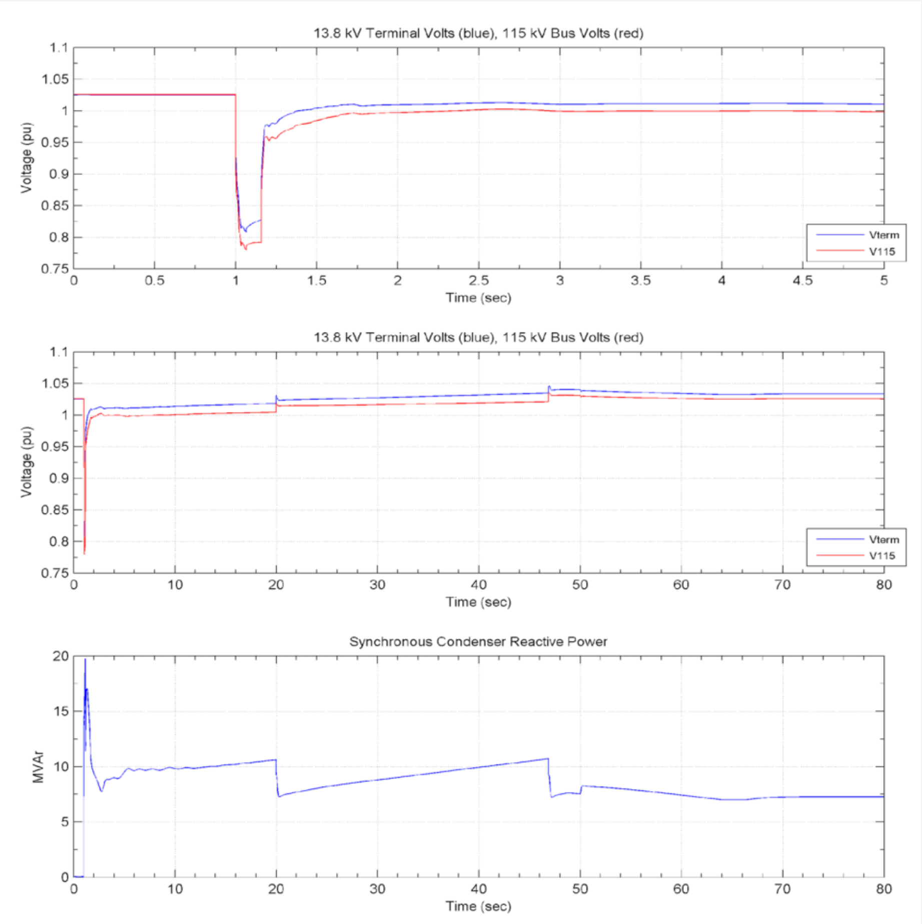
Simulation of a loss of 345 kV

Synchronous Condensers

First 5 seconds

Longer time scale

- Synchronous condensers (dynamic Vars) react quickly to low voltage in < 1sec.
- Shunt capacitors (static Vars) switch in at 20 and 48 seconds; offset VARs.

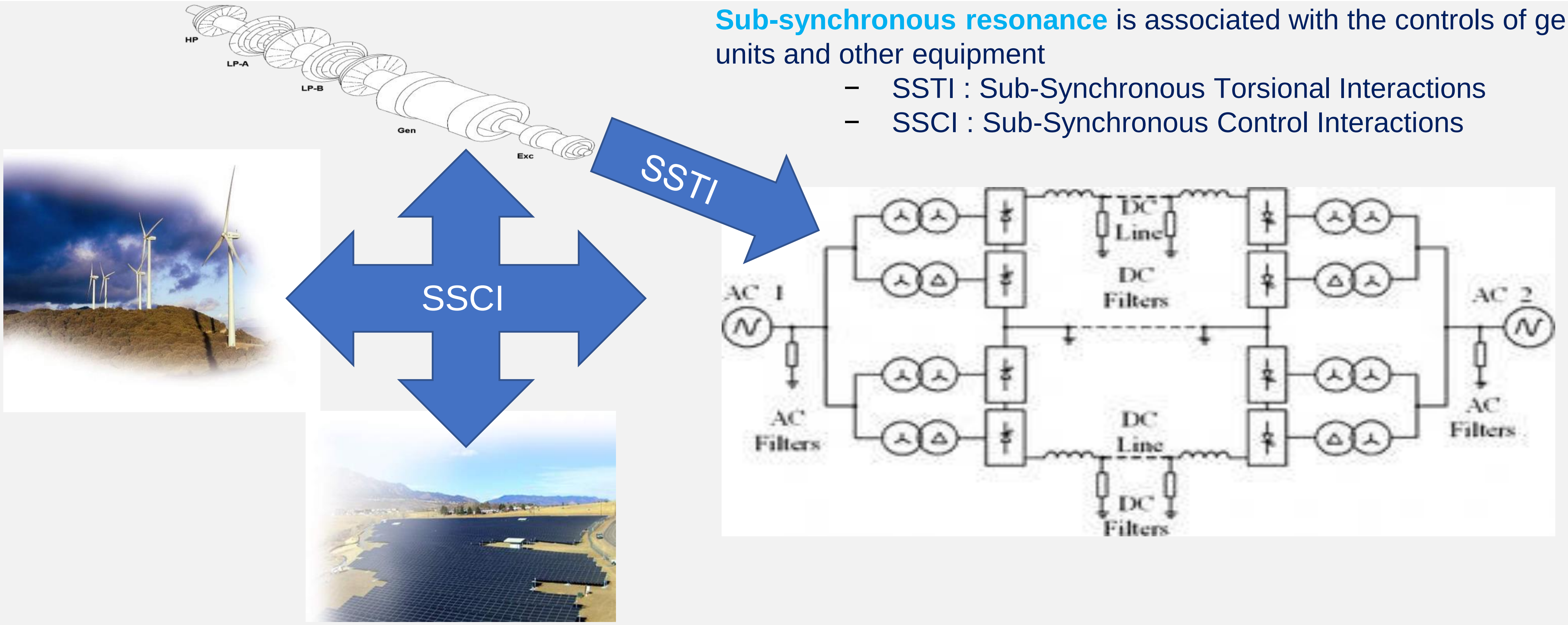


Sub-synchronous Oscillations

Large STG, HVDC and RE interconnection

Sub-synchronous resonance is associated with the controls of generating units and other equipment

- SSTI : Sub-Synchronous Torsional Interactions
- SSCI : Sub-Synchronous Control Interactions

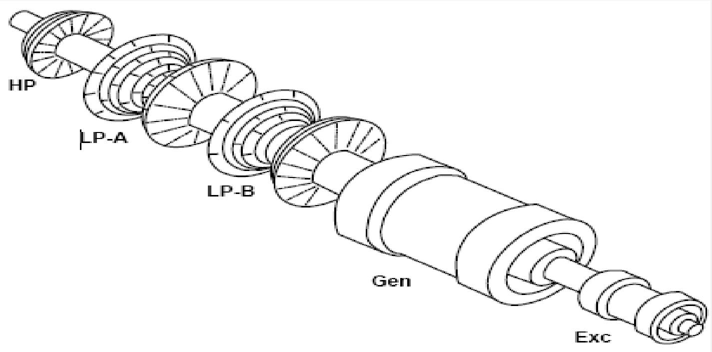


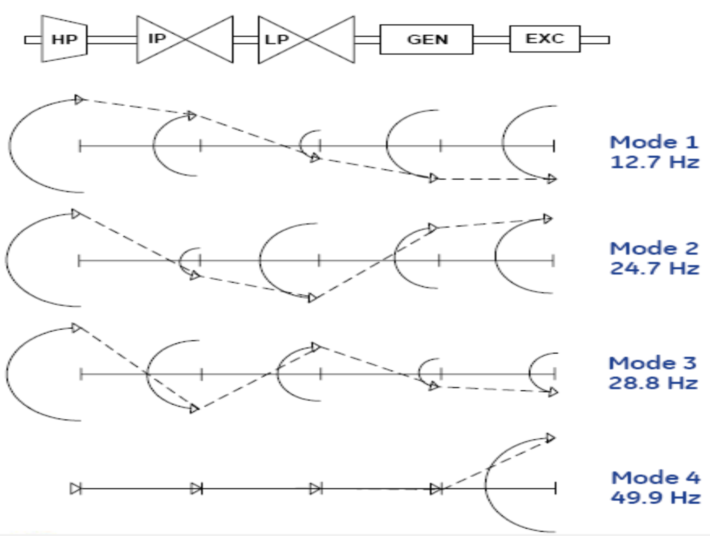
Sub-synchronous oscillations

- Sub-synchronous oscillation is an electric power system condition where a significant energy exchange takes place at one or more of the natural frequencies of the combined turbine-generator system below the synchronous frequency following a disturbance in the grid.
- Involve interaction between the electrical and mechanical energies coupled through the generator.
- Involves different masses on the turbine-generator rotor.
- Generally in the range of 15-55 Hz (for a 60 Hz grid).

Sub-synchronous oscillations

- Large thermal units - connected to series-compensated AC or HVDC or RE technology.
- Frequencies and mode shapes determined by shaft geometry.
- Very low inherent damping.
- The rotor masses and coupling shafts form a spring-mass system having intrinsic modes of torsional natural frequencies.
- m-1 modes of torsional oscillations for an m-mass-spring system, in addition to a zero mode.
- Disturbances may cause the turbine-generator shaft to oscillate at one or more of its modes of torsional oscillations.





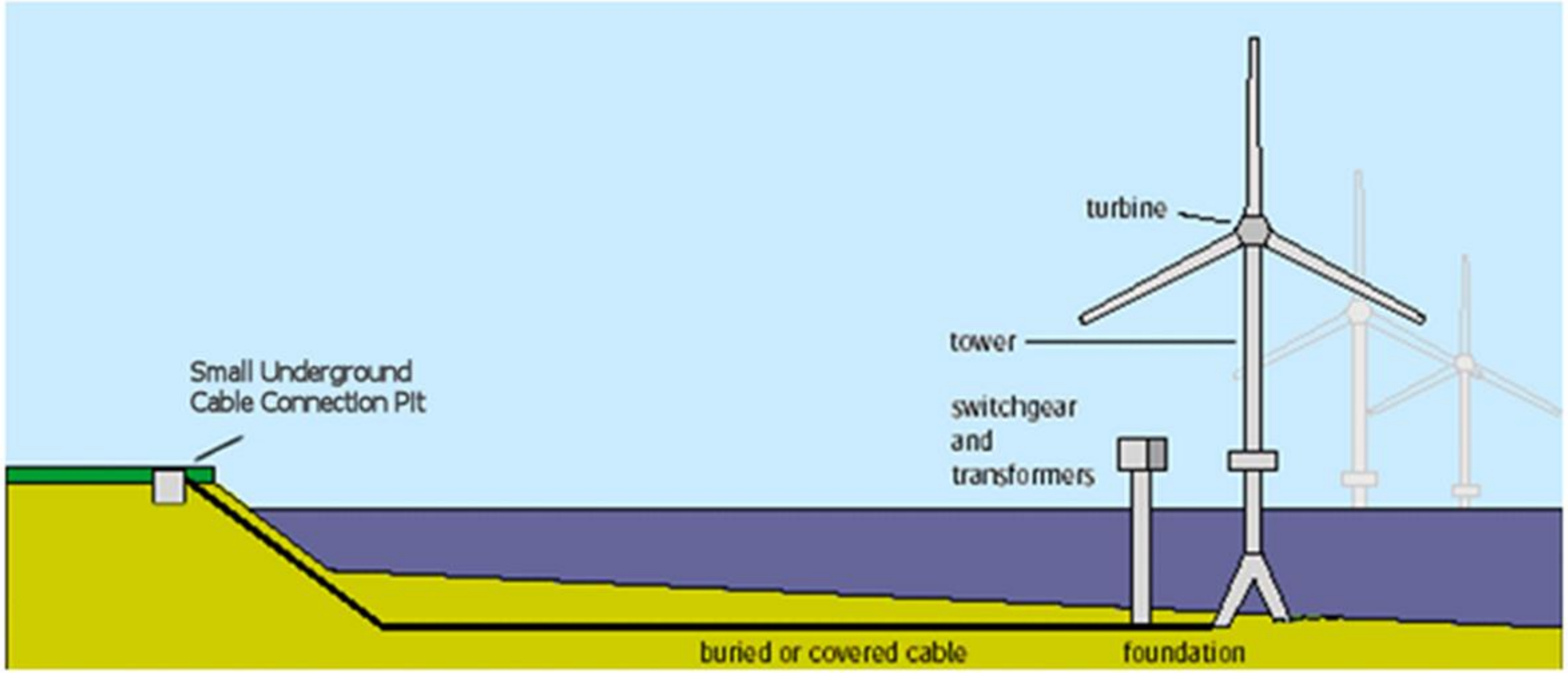
Sub-synchronous oscillations

- Suitable mitigation measures need to be adopted:
  - A thorough SSR screening study needs to be carried out
  - Power Plant Control design for RE may have to be modified
  - Compensation level of series compensated HVAC lines may need to be altered
  - Thyristor trigger frequency for HVDC may need to be altered
  - Re-routing of interconnection (if possible) may need to be considered

Transmission Network for offshore WTG

Offshore WTG

Figure 2.1 Components of a Typical Offshore Wind Farm

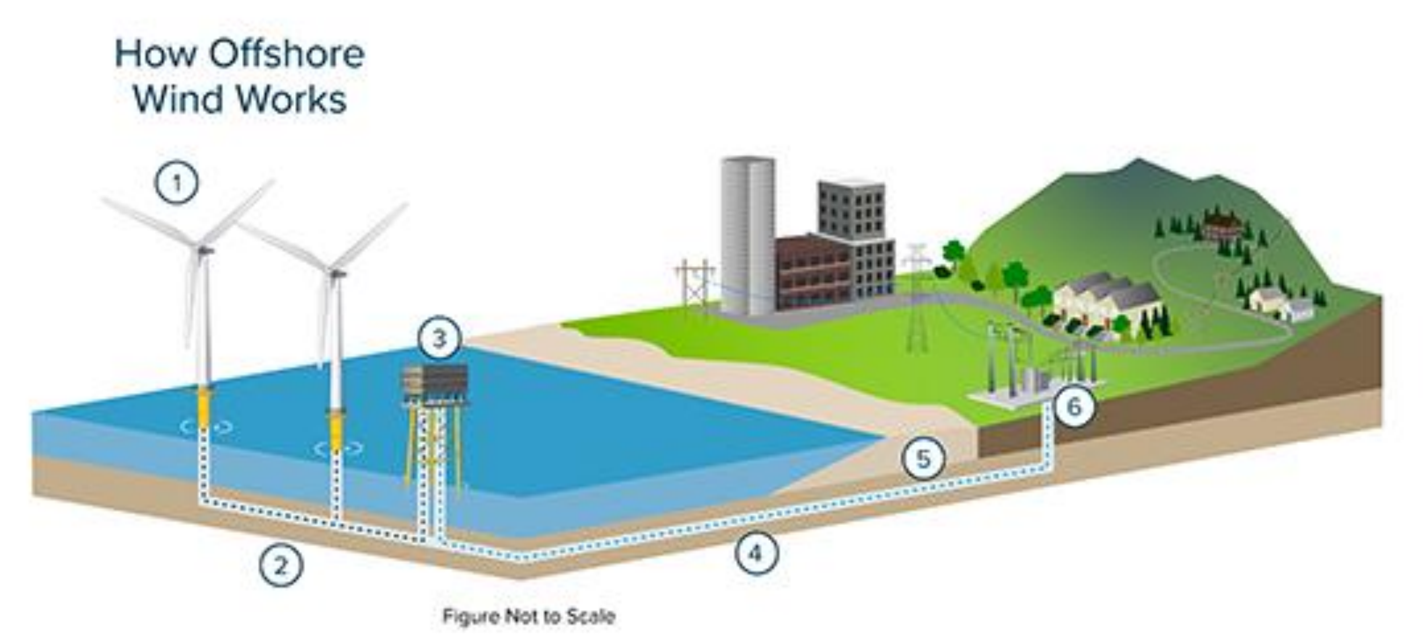


Source: *UK Department of Trade & Industry (DTI), 2002.*

Offshore wind income

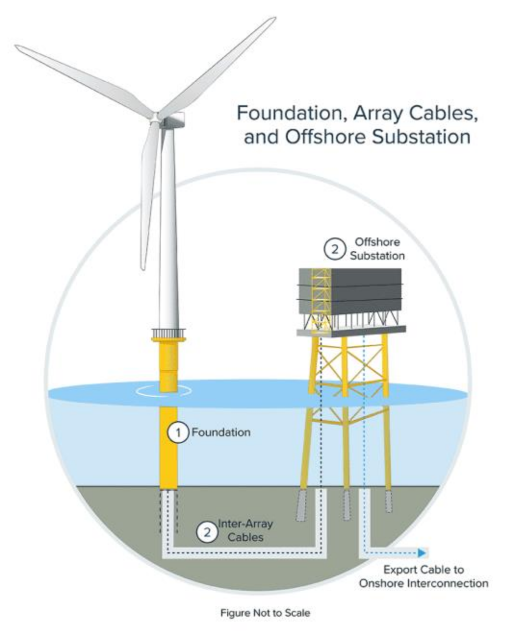
Country	UK	Germany	Denmark	Belgium	Netherlands	France
Name of scheme	Contracts For Difference	Einspelsevergutung (§ 50 EEG)	Public Service Obligation (PSO)	Groenestroom Certification	SDE+	Renewable Energy Directive Offshore
Installed capacity (GW)	4.0	2.8	1.3	0.7	0.2	0.0
Target capacity 2020 (GW)	~11.0	6.5	2.2	2.2	1.6	6.0
Subsidy type						
Subsidy payment per kwh	Guaranteed price (strike price) less electricity market price	Base guaranteed price less electricity market price	Guaranteed price less electricity market price	Guaranteed price less electricity market price which is reduced by ~10%	Required price less guaranteed price plus imbalance and profile factor and capped	Guaranteed price (Feed-in-tariff depending on tender round, location, bid)
Guaranteed price € cents/kwh	Strike price = Highest price in an auction (pay as cleared) Now 16.0	Based on pre-determined average, Now 15.4 (first 12 years) then 0.039 (to year 20)	Project specific determined in an auction, Now 8.44 – 14.10	Based on predetermined average, Now 13.8	Project specific determined in an auction, Now 8.44 – 14.10	Project specific Now 15.0 – 22.0
Guaranteed price is index linked	Yes, Consumer Price Inflation	NO				Yes, Consumer Price Inflation

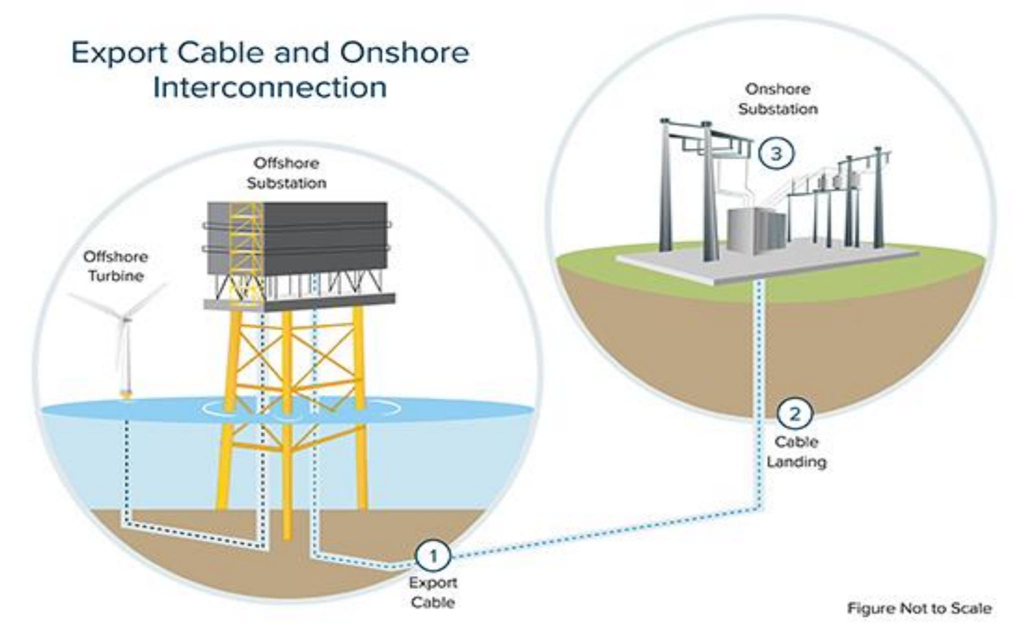
Transmission network for offshore WTG



1. Offshore Turbines capture the wind's energy and generate electricity.
2. Foundations secure turbines to the ocean floor and cables transmit electricity to an offshore substation.
3. Electricity flows through a buried cable to an onshore substation and is transferred to the existing transmission network.

Offshore transmission





1. **Export Cable**: buried deep enough to avoid disturbing ocean users and wildlife, and it transmits power from the offshore substation to the onshore substation.
2. **Cable Landing:** horizontal direction drilling, a common method for landing export transmission cables from offshore wind farms, minimizes environmental impacts and disruption to beaches and the shoreline.
3. **Onshore Connection:** electricity is transferred to the existing transmission network.

Responsibility and ownership

- Who builds, owns and operates offshore electrical transmission infrastructure?
  - Offshore wind farm developer, or
  - The grid operator?

HVDC Transmission System

HVDC transmission systems

- In certain applications and scenarios, HVDC transmission offers distinct economic and or performance advantages for:
  - Long distance overhead transmission
  - Underwater or underground transmission
  - Asynchronous ties between power systems

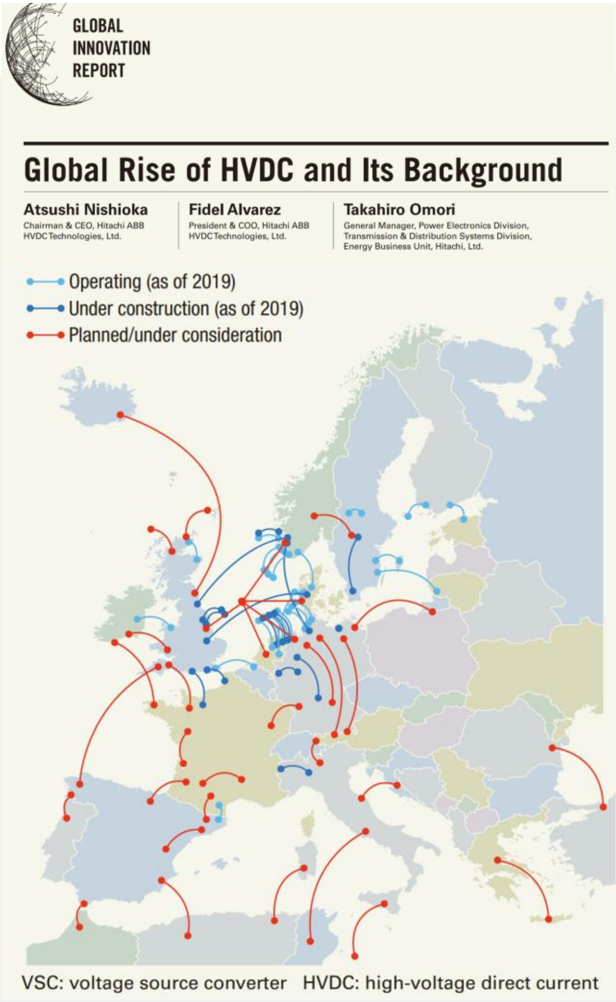
- First Application in Sweden in 1954, wider application after 1960.
  - England and France.
  - California-Oregon ±500 kV.

HVDC transmission systems

- HVDC deployment is growing due to their advantages such as:
  - More stable and robust than existing HVAC systems
  - Increase the transmission capacity
  - Reduces power losses through the line

- Integrating large-scale solar PV systems into the power grid presents challenges related to power loss, reduced transmitted power capacity, and grid stability due to intermittency behavior.

- HVDC transmission systems offer efficient and reliable power transmission over long distances, making them suitable for connecting remote RESs to load centers.



GLOBAL
INNOVATION
REPORT

Global Rise of HVDC and Its Background

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Chairman & CEO, Hitachi ABB HVDC Technologies, Ltd.

Fidel Alvarez
President & COO, Hitachi ABB HVDC Technologies, Ltd.

Takahiro Omori
General Manager, Power Electronics Division, Transmission & Distribution Systems Division, Energy Business Unit, Hitachi, Ltd.

VSC: voltage source converter HVDC: high-voltage direct current

Impact due to Underutilization of Transmission Network

Challenges with underutilization

- Improper characterization of utilization can result in over or under building of power system facilities and stressing of system equipment beyond design capabilities.
- A number of terms are used to characterize the magnitude and intensity of loads. The terms include energy, demand, demand factor and load factor.
- It is inefficient to invest in new equipment to deal with the short peak output of renewable energy generation.
- Transmission system utilization is the retrospective result of forward-looking transmission planning practices that balance the objectives of achieving good system utilization while maintaining unutilized capacity to meet future needs.
- Transmission utilization and transmission capability are the same concept but viewed from different perspectives.

Concepts of underutilization

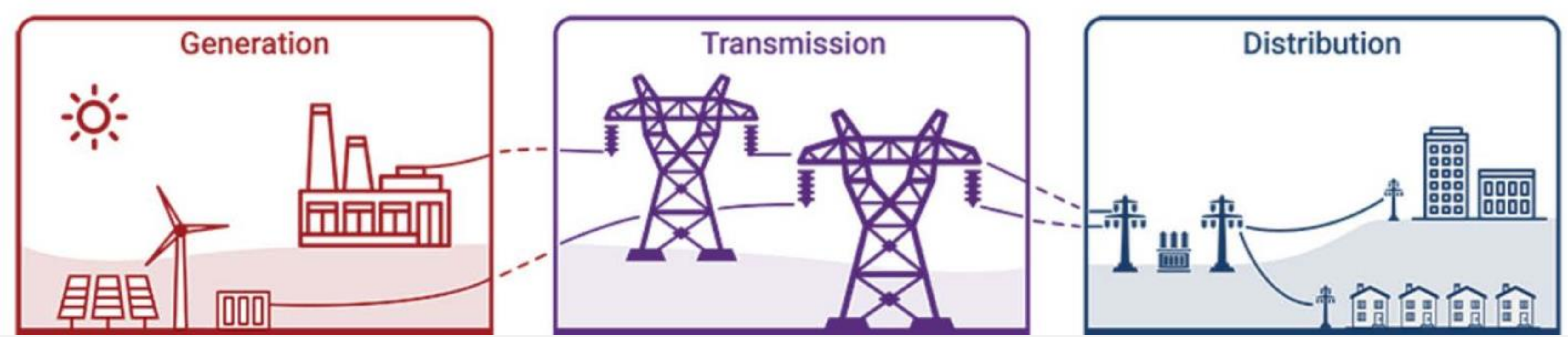
Four key concepts of transmission utilization:

- Capacity margin to accommodate future transmission system needs
- Reliability margin to facilitate reliable operation of the transmission system
- Capacity used for power flow which facilitates fluctuating power flows through the facility over time
- Capacity that cannot be utilized at the facility level due to system constraints, such as system operating limits.

Improving the utilization

- Switching to the reactive grid operation concept, huge batteries are used to quickly resolve overloading of transmission lines, but in contrast to current operation procedures, only after an actual contingency event.
- The grid booster assets react very fast - within 150 milliseconds – to inject or absorb critical power as part of the transmission grid in case of power system component failures.
- As batteries take over this critical role to resolve the immediate impact during power system contingency events, as shown in the graph below, the previously not fully utilized transmission lines can now be used at an increased capacity.
- This can reduce grid congestion and prevent expensive curtailment and congestion management that was previously required.

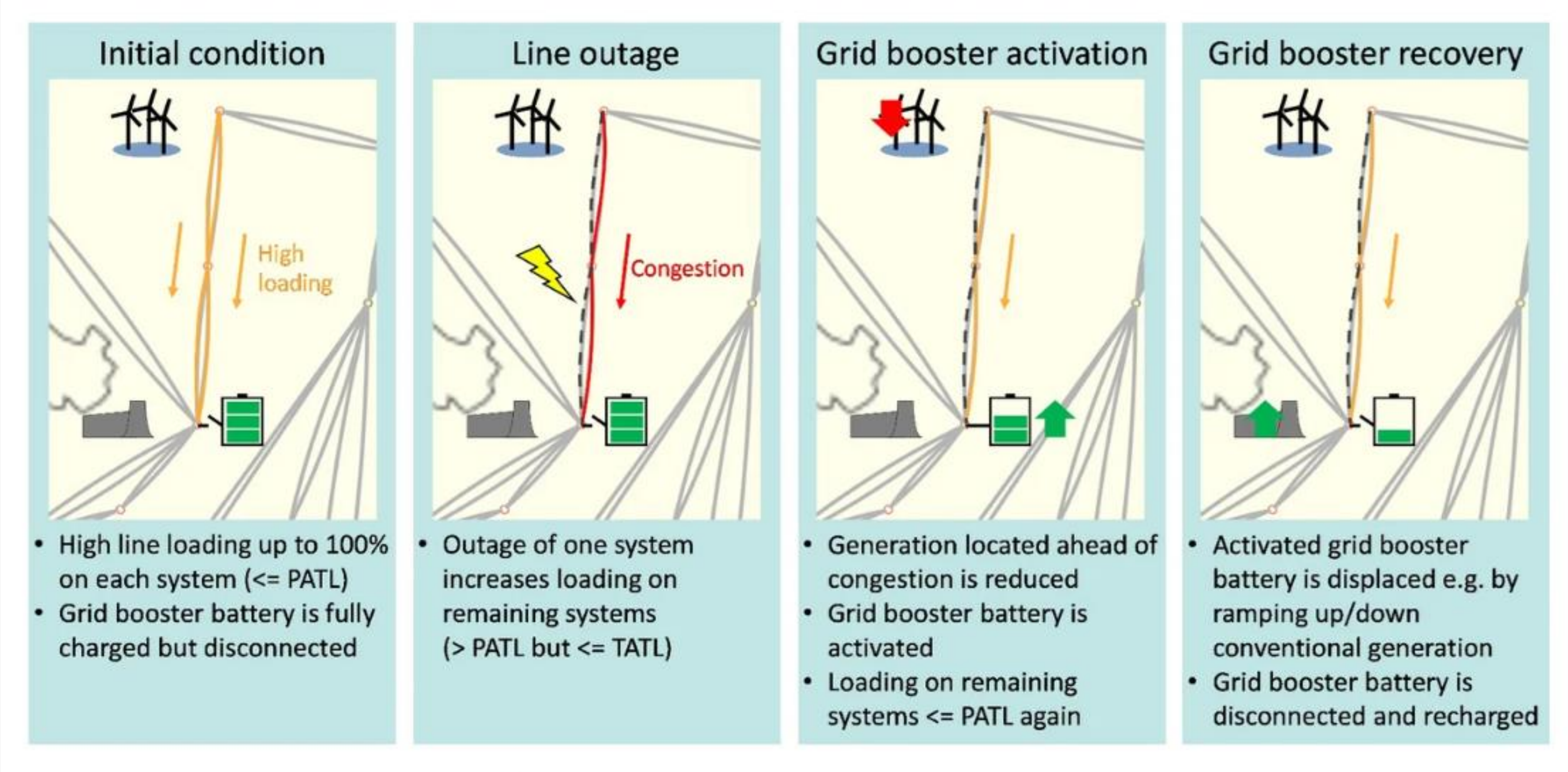
Role of BESS



- Address supply disruptions
- Address variability of RE sources
- Provide peaking capacity

- Defer transmission upgrade
- Relieve transmission congestion
- Provide grid (ancillary) services

Optimal utilization reduces grid costs



Initial condition

- High line loading up to 100% on each system (<= PATL)
- Grid booster battery is fully charged but disconnected

Line outage

- Outage of one system increases loading on remaining systems (> PATL but <= TATL)

Grid booster activation

- Generation located ahead of congestion is reduced
- Grid booster battery is activated
- Loading on remaining systems <= PATL again

Grid booster recovery

- Activated grid booster battery is displaced e.g. by ramping up/down conventional generation
- Grid booster battery is disconnected and recharged

Basic Principle of the Reactive Grid Operation Concept (Schematic Illustration)

Economic Aspects

Economic approach

New models and approaches have surfaced to formulate and quantify the cost of renewable energy on the overall transmission cost. Complicated models can include factors such as:

- K = the capacity at both the remote and BBS in MW.
- C = the cost of K in \$/MWh.
- f_R = the capacity factor at the remote site.
- Q_R = the average power output at the remote location in MW (f_R • K).
- C_R = the cost of producing Q_R per MWh (= C K/Q_R= C/f_R).
- f_B = the capacity factor at the BBS.
- Q_B = the average output from K at the BBS in MW (f_B• K).
- C_B = Sie cost per MWh of producing Q_B per MWh (=C K/Q_B = C/f_B).

Economic approach

- $Q_T = Q_R - Q_B$ = the average output produced by the transmission line in MW.
- CQ_T = the cost per MWh of producing Q_T.
- C_T = the cost per MWh of transmitting Q_R over the new remote transmission line.

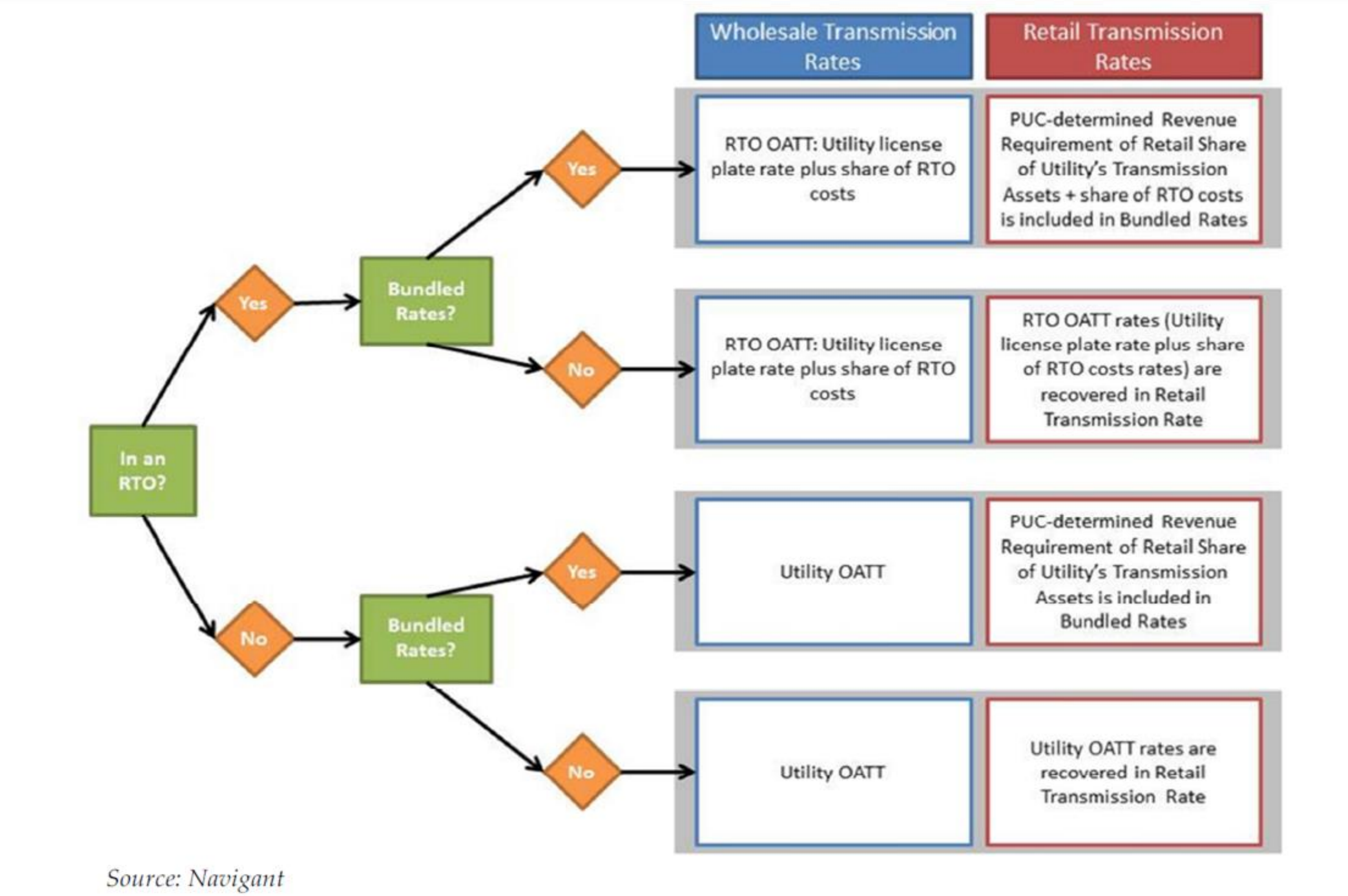
Any case, the cost, CQ_T, of renewable energy produced by this remote transmission is

- $CQ_T = C_T\ Q_B / Q_T$ [measured in US$/MWh]

Example

- This can be understood by an example.
  - Suppose the cost of transmission is US$10/MWh, and it is transmitting 100 MW on average.
  - This is a cost of C_T x Q_R = US$1,000/h.
  - If it is only "producing" 25 MW, it is costing US$1,000/h to obtain these extra 25 MW,
  - so the cost is (US$1,000/h)/(25 MW) = US$40/MWh.
- In the previous example, transmission costs US$5/MW for 120 MW, but only 20 MW was produced by the line, so that comes to 5 x 120 / 20 = US$30/MWh, just as before.
- Note that as Q_T approaches zero, the benefit of the line approaches zero and so the cost per megawatt-hour produced approaches infinity.

Transmission cost recovery

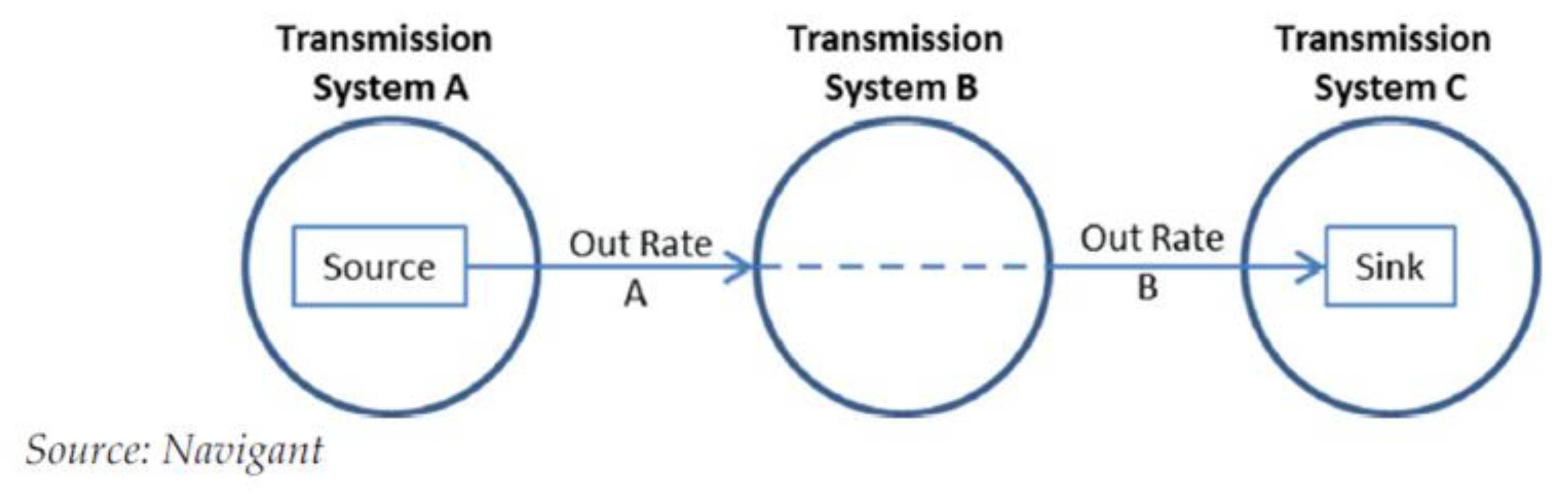


Source: Navigant

Rate pancaking

Rate Pancaking Example

Rate Pancaking: Additional charge for each transmission system a power transaction is contracted to pass through: Source in A, Sink in C, pay out rates for both system A and B

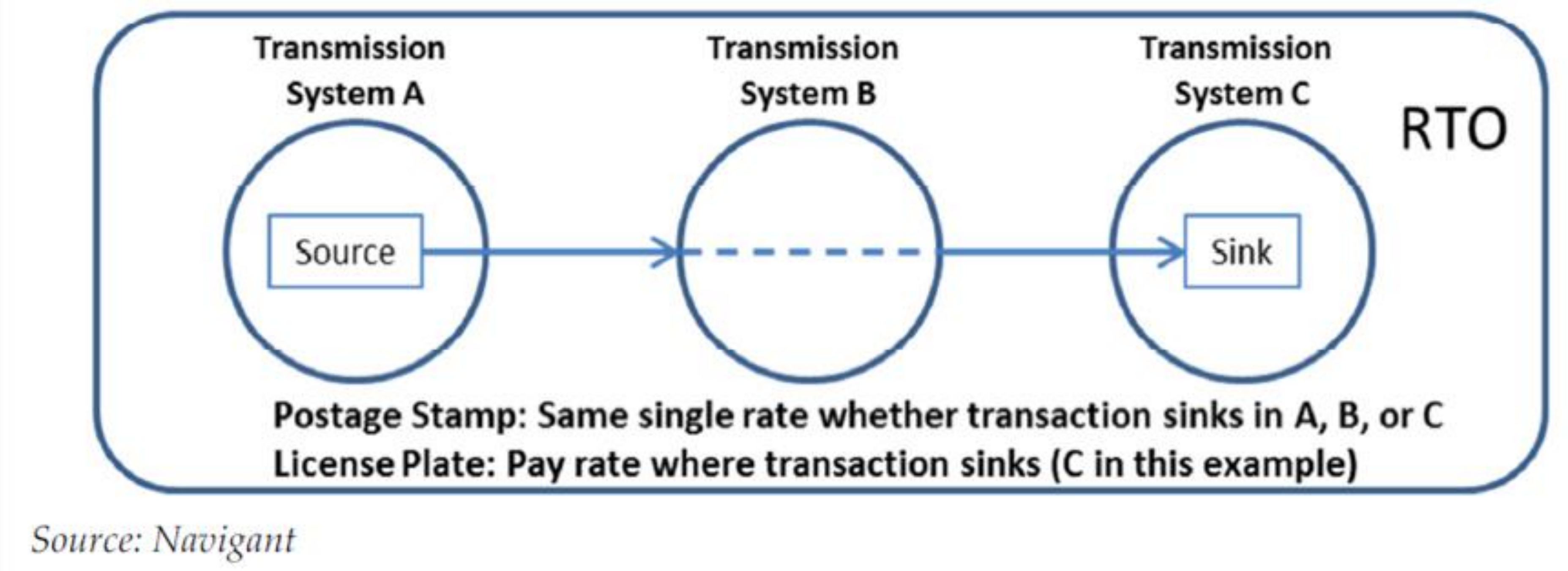


Source: Navigant

Postage stamp rating

RTO Postage Stamp and License Plate Rate Example

Postage Stamp: Pay same rate no matter where power transaction sinks within RTO
License Plate: pay rate of system where power transaction sinks within RTO



Postage Stamp: Same single rate whether transaction sinks in A, B, or C
License Plate: Pay rate where transaction sinks (C in this example)

Source: Navigant

Overview of cost allocation methods

	Broad Socialization	Flow-Based	Economic Value	Localized
Facility-types typically allocated	High-voltage long distance lines	Lower-voltage facilities solving regional reliability issues	Lines constructed for economic efficiency reasons	Low-cost projects solving local reliability issues
Administrative ease & understandability	Easy/Simple	Harder, need complex reliability modelling	Harder, need complex economic modelling	Easy/Simple
Directly quantifies whether those that benefit are paying?	No, unless modelling is also performed	Yes	Yes	Not needed

Source: Navigant

Summary

- Development of transmission networks must align with RE generation installation to maximize the benefits.
- Wind and solar resources smooth out with geographic diversity.
- Large interconnections involving multiple countries would support higher RE generation.
- Voltage and inertial support can be provided through synchronous condensers.
- Batteries can provide important ancillary service at the transmission level.
- A regional level study to develop a roadmap for large interconnections would be important.

Questions?

Economic and Social Commission for Western Asia

Integration Costs of Wind and Solar Power

Impact of RE on Distribution Systems

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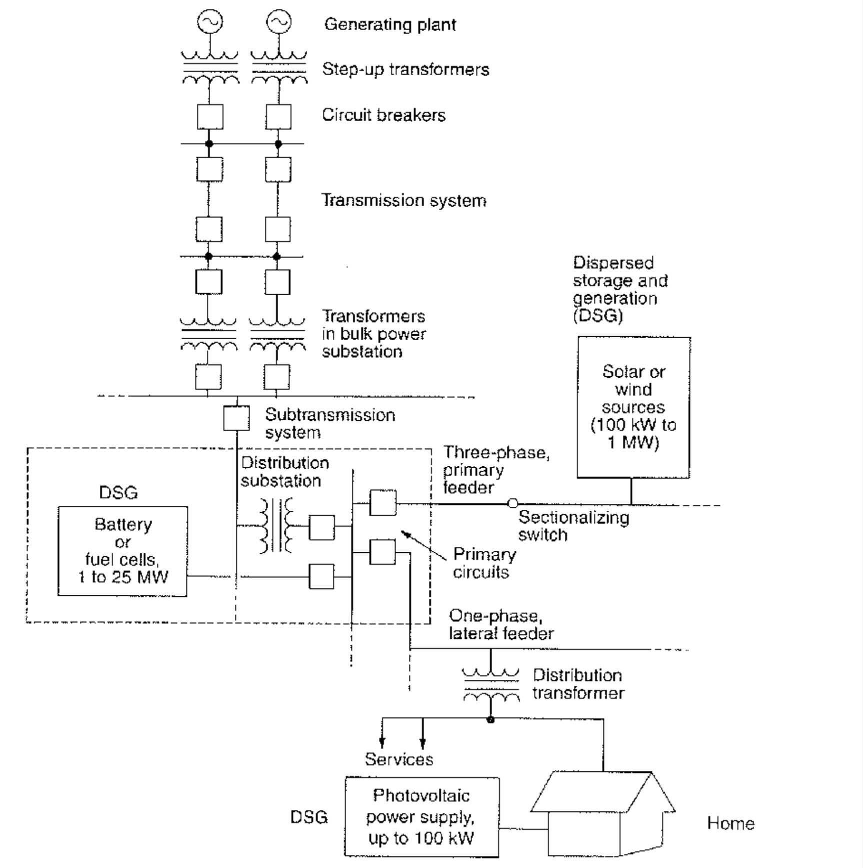
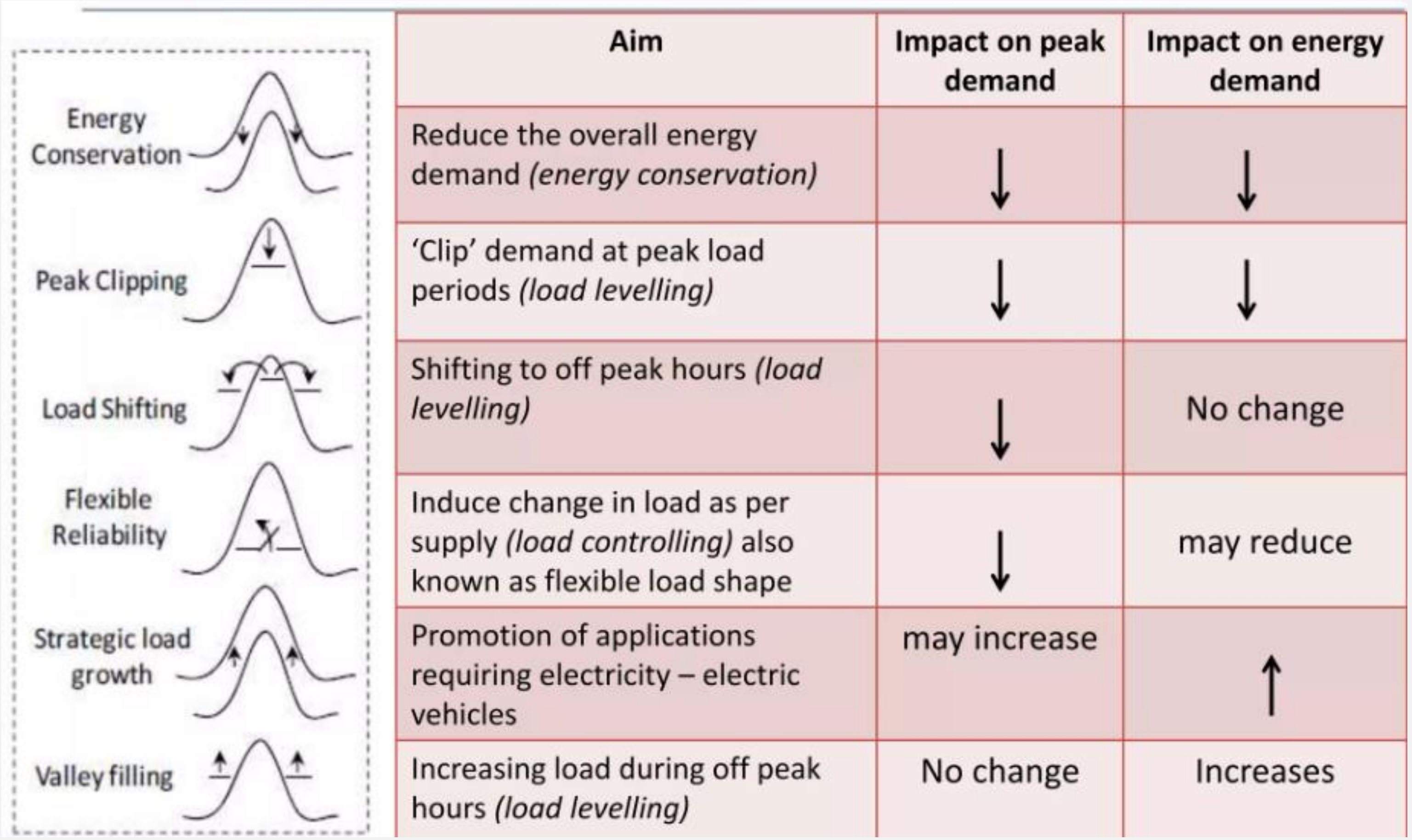
Impact of RE on Distribution System and Solutions

Impact of distributed generation



Demand side management



	Aim	Impact on peak demand	Impact on energy demand
Energy Conservation	Reduce the overall energy demand *(energy conservation)*	↓	↓
Peak Clipping	'Clip' demand at peak load periods *(load levelling)*	↓	↓
Load Shifting	Shifting to off peak hours *(load levelling)*	↓	No change
Flexible Reliability	Induce change in load as per supply *(load controlling)* also known as flexible load shape	↓	may reduce
Strategic load growth	Promotion of applications requiring electricity – electric vehicles	may increase	↑
Valley filling	Increasing load during off peak hours *(load levelling)*	No change	Increases

Flexible loads

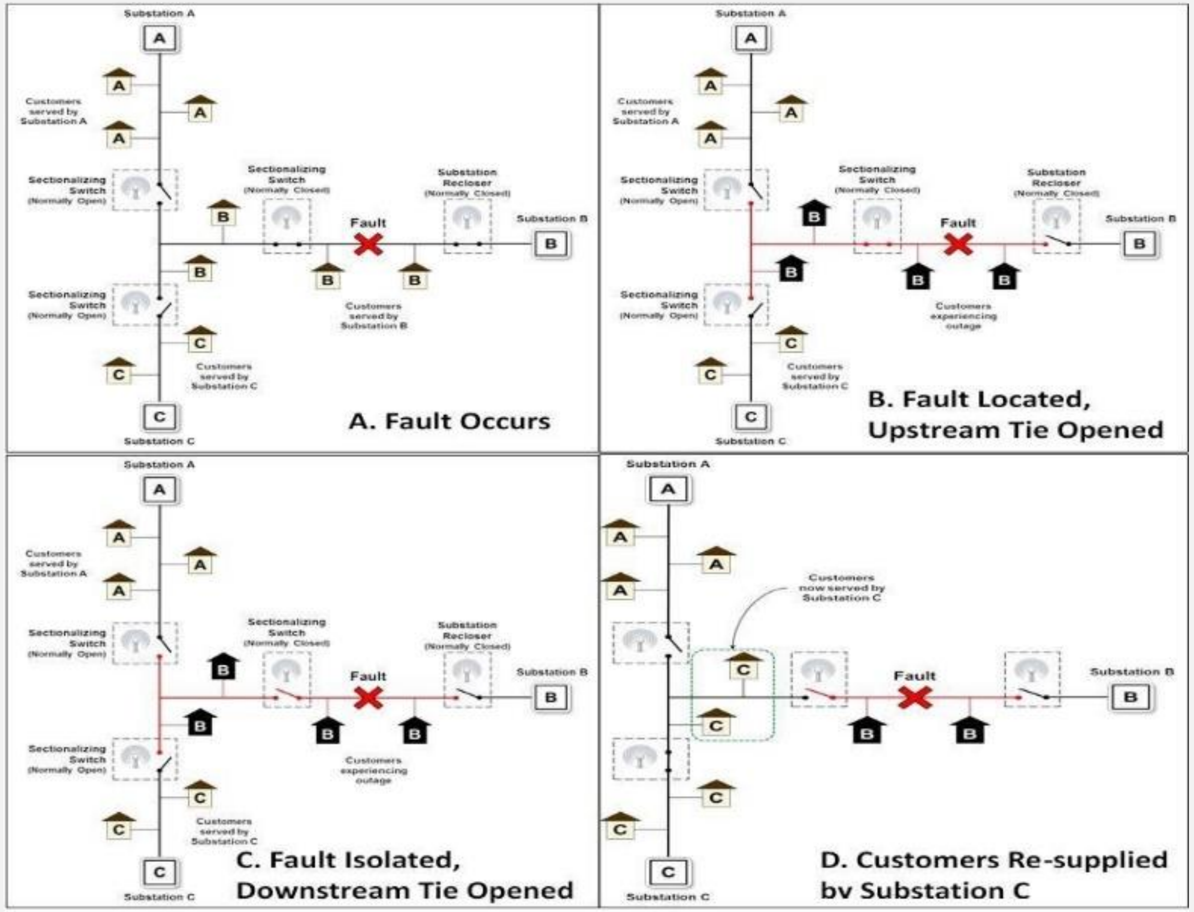
- On the consumption side, there are opportunities to utilize more flexible loads to support grid operation and planning.
- Traditionally-passive consumption devices are evolving to smartly respond to grid conditions.
- Air conditioners, gas furnaces, and water heaters can adjust their thermostat settings to decrease consumption when the grid is under stress.
- Refrigerators and lights are also incorporating smart settings.
- EVs can charge or not charge depending on electricity price or other incentive signals

Advanced SCADA System

Fault location isolation and service restoration (FLISR)

Fault Location Isolation and Service Restoration (FLISR) Scheme

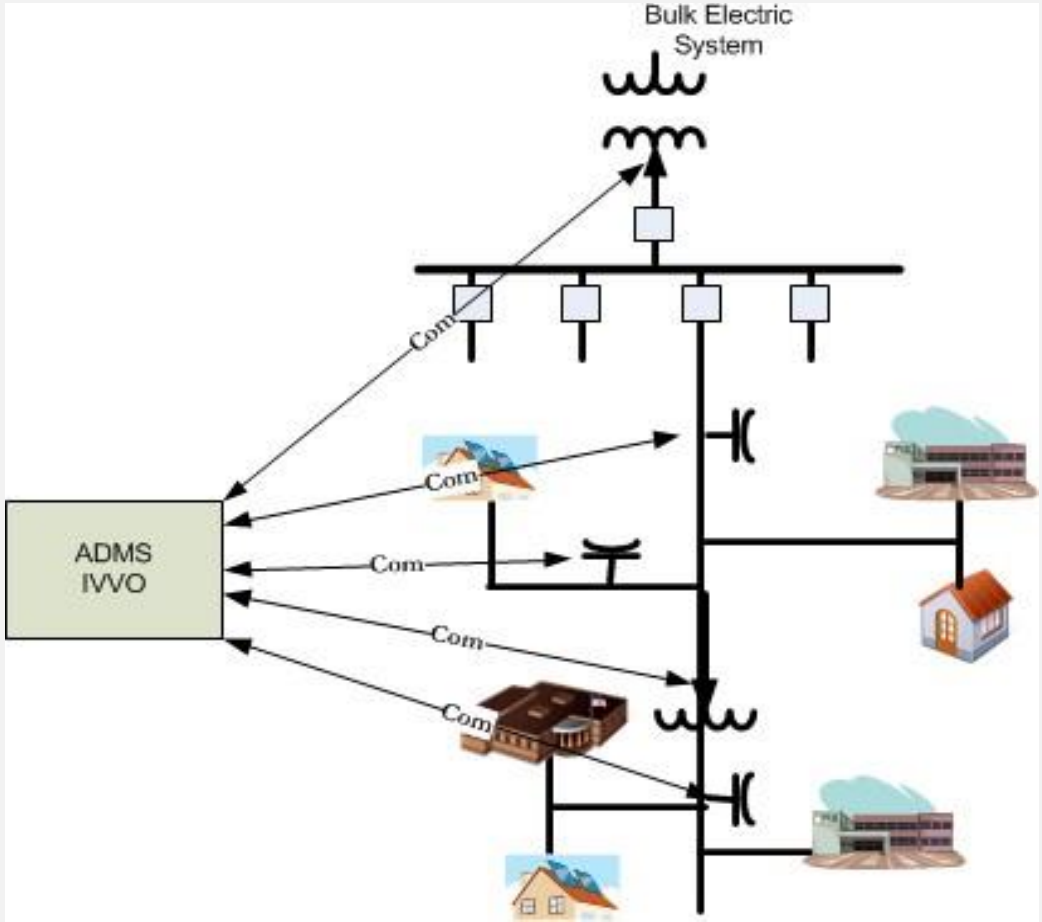
- FLISR scheme creates several sections of the network.
- It improves the fault location and restoration time and improves system availability and the key indices like System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI).
- Some of the case studies indicate that FLISR can potentially reduce the system restoration time to 50%.



Integrated voltage and var optimization (IVVO)

Integrated Volt Var Optimization (IVVO)

- Due to high penetration of renewables, the voltage across the network varies significantly.
- IVVO performs the power flow and suggests the requirement (location and size) of Var resource to be added/withdrawn from the circuit to achieve flat voltage profile thus optimizing the Var requirement.

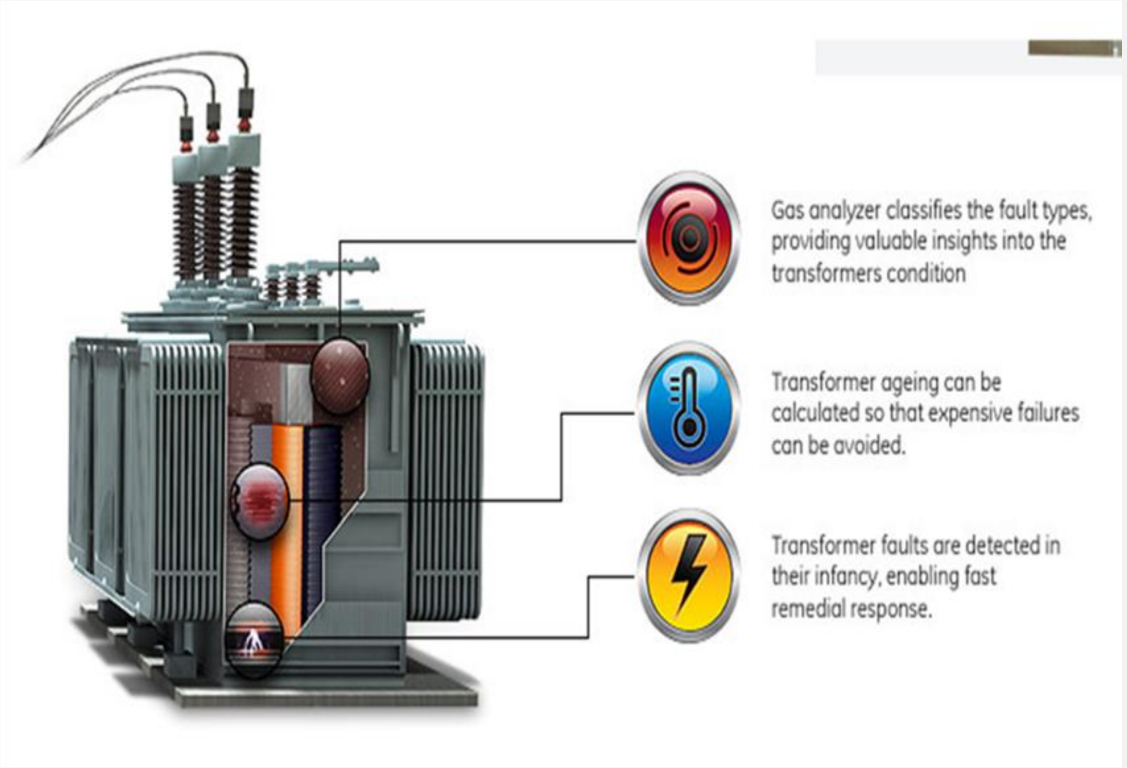


IoT Applications

Transformer

On-line Dissolved Gas Analysis (DGA)

- Major transformer internal faults result in development of gases that ultimately operate Buchholz relay.
- On-line DGA can track the development of these gases and provide alert as the gases hit alarming levels that indicate the development of a fault.
- On-line monitoring can extend the maintenance intervals.
- It extends the life of the transformer.
- Implement online-DGA in oil filled transformers transformers.



Gas analyzer classifies the fault types, providing valuable insights into the transformers condition

Transformer ageing can be calculated so that expensive failures can be avoided.

Transformer faults are detected in their infancy, enabling fast remedial response.

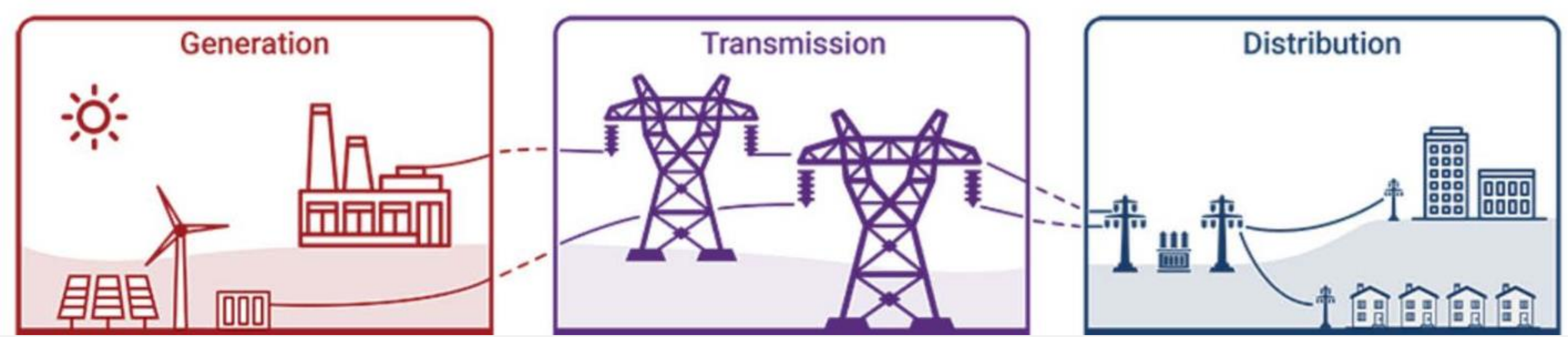
Grounding

On-line Ground Resistance Monitoring

- Ground resistance indicates the effectiveness of grounding.
- Generally, audits are carried out annually to assess the condition of earth pits.
- On-line grounding resistance monitoring can help in understanding the health of the pits and can help in fixing only those pits which show higher degradation.
- On-line monitoring can extend the maintenance intervals.
- Install on-line grounding monitoring system in key sub-stations and integrate with SCADA.

Role of Battery Energy Storage System (BESS)

Role of BESS

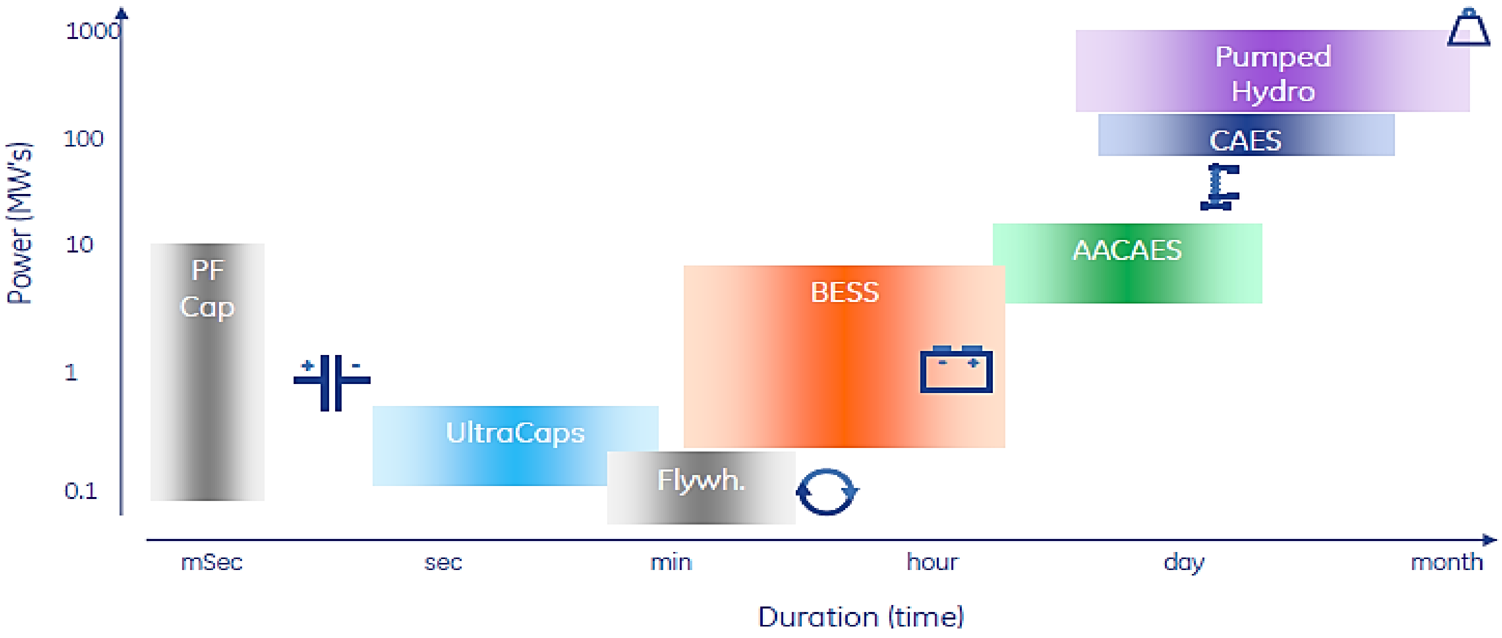


- Address supply disruptions
- Address variability of RE sources
- Provide peaking capacity

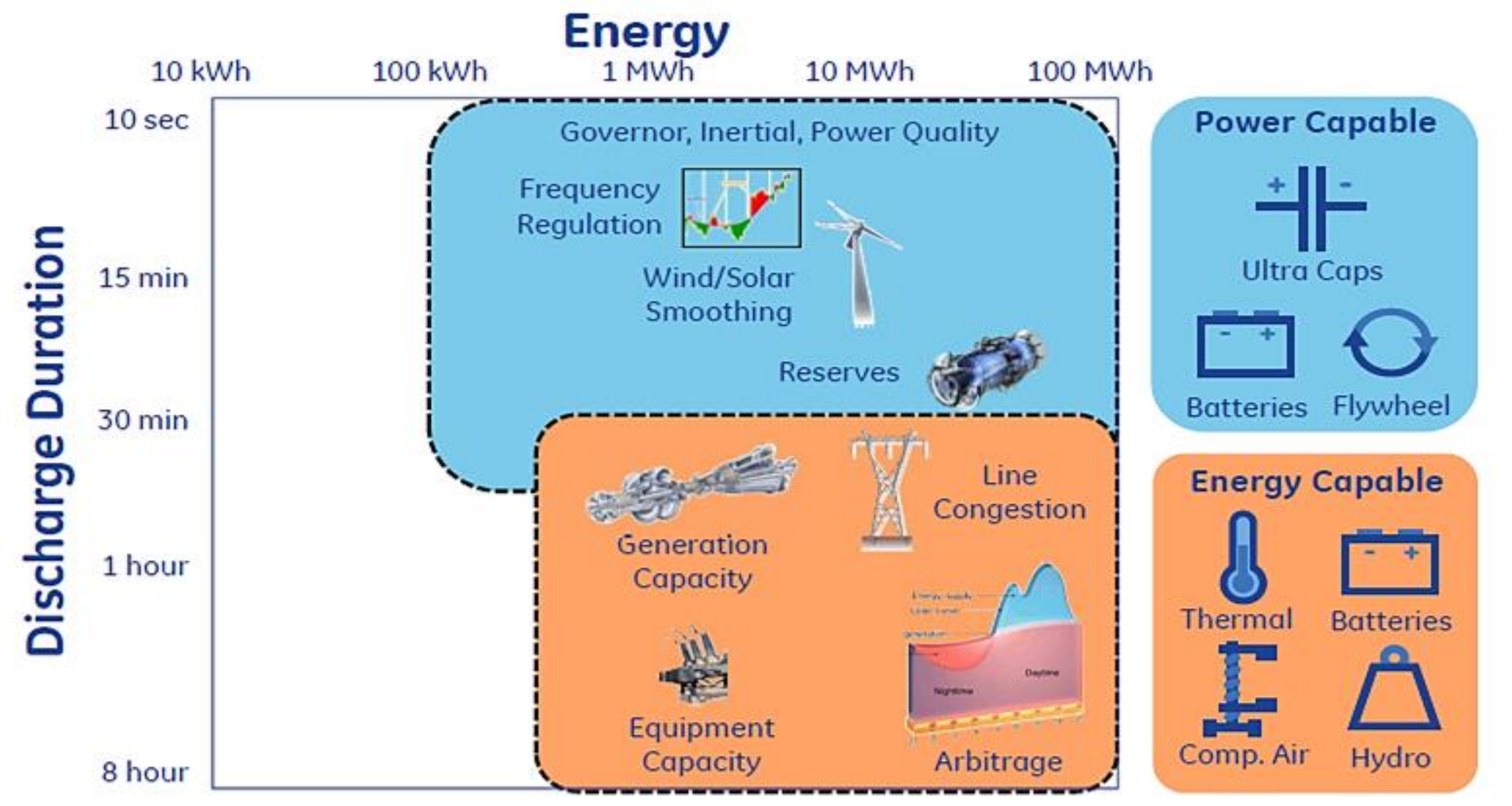
- Defer transmission upgrade
- Relieve transmission congestion
- Provide grid (ancillary) services

- Defer distribution upgrade
- Provide back-up power during outages
- Support microgrids

Energy Storage



Energy Storage Applications

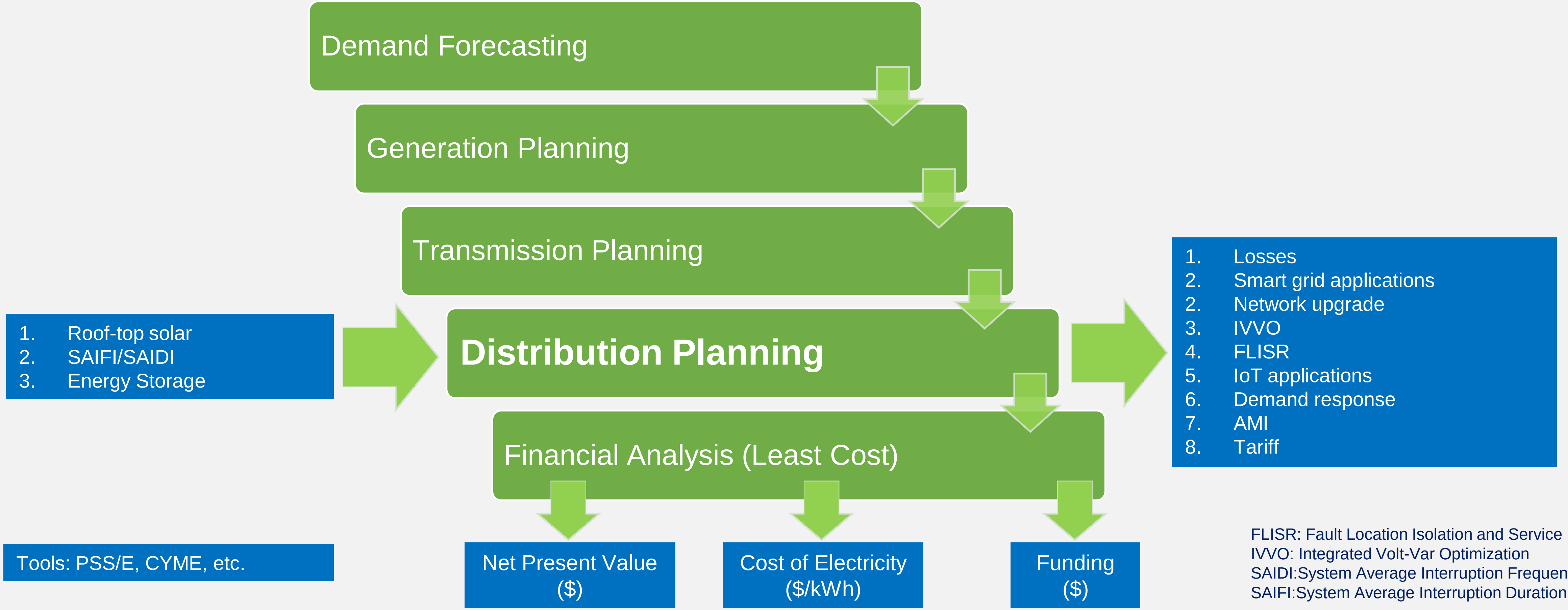


Distributed BESS

- When coupled with a renewable distributed energy generation source (e.g., solar PV), battery storage can provide backup generation for extended periods of time (days to weeks):
    - Decreases the size of other backup generation (e.g., diesel generators) and extends limited fuel supply.
    - Is a fully renewable backup power source (when coupled with renewables) that does not need refueling.
    - Can provide revenue streams while grid connected (e.g., demand charge reduction, demand response programs, energy arbitrage, etc.).

Impact on Distribution Planning

Distribution planning



Demand Forecasting

Generation Planning

Transmission Planning

Distribution Planning

Financial Analysis (Least Cost)

1. Roof-top solar
2. SAIFI/SAIDI
3. Energy Storage

1. Losses
2. Smart grid applications
2. Network upgrade
3. IVVO
4. FLISR
5. IoT applications
6. Demand response
7. AMI
8. Tariff

Tools: PSS/E, CYME, etc.

Net Present Value ($)

Cost of Electricity ($/kWh)

Funding ($)

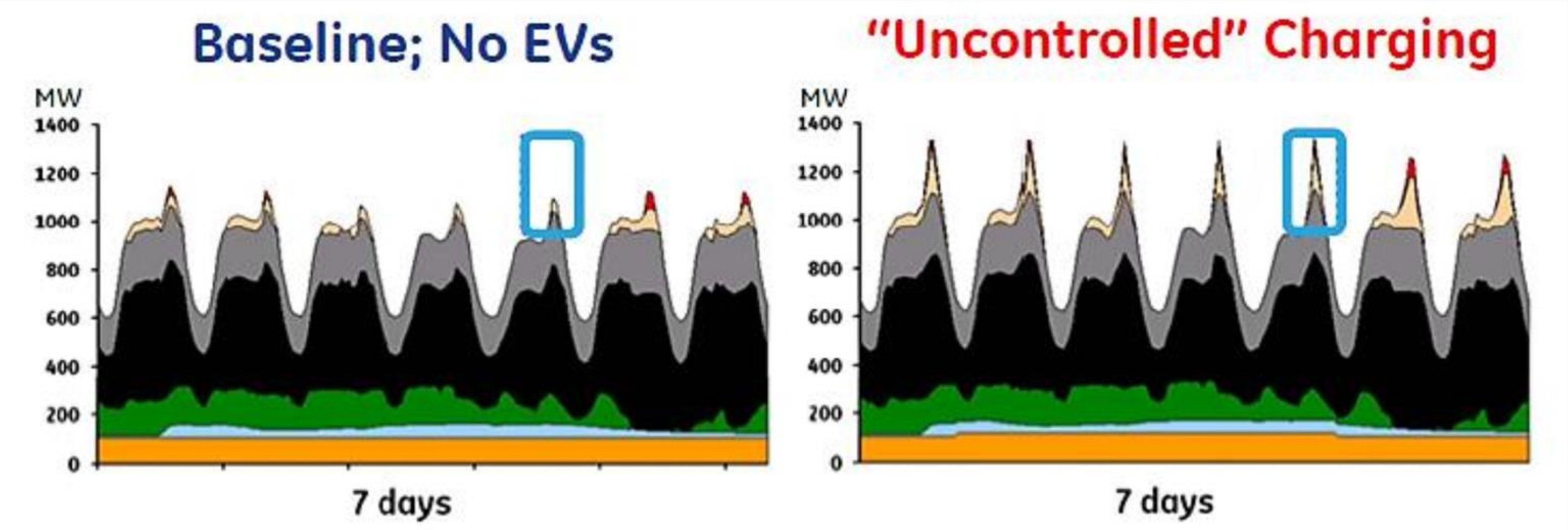
FLISR: Fault Location Isolation and Service Restoration
IVVO: Integrated Volt-Var Optimization
SAIDI:System Average Interruption Frequency Index
SAIFI:System Average Interruption Duration Index

Impact of Electric Vehicles (EV)

Key questions around EV

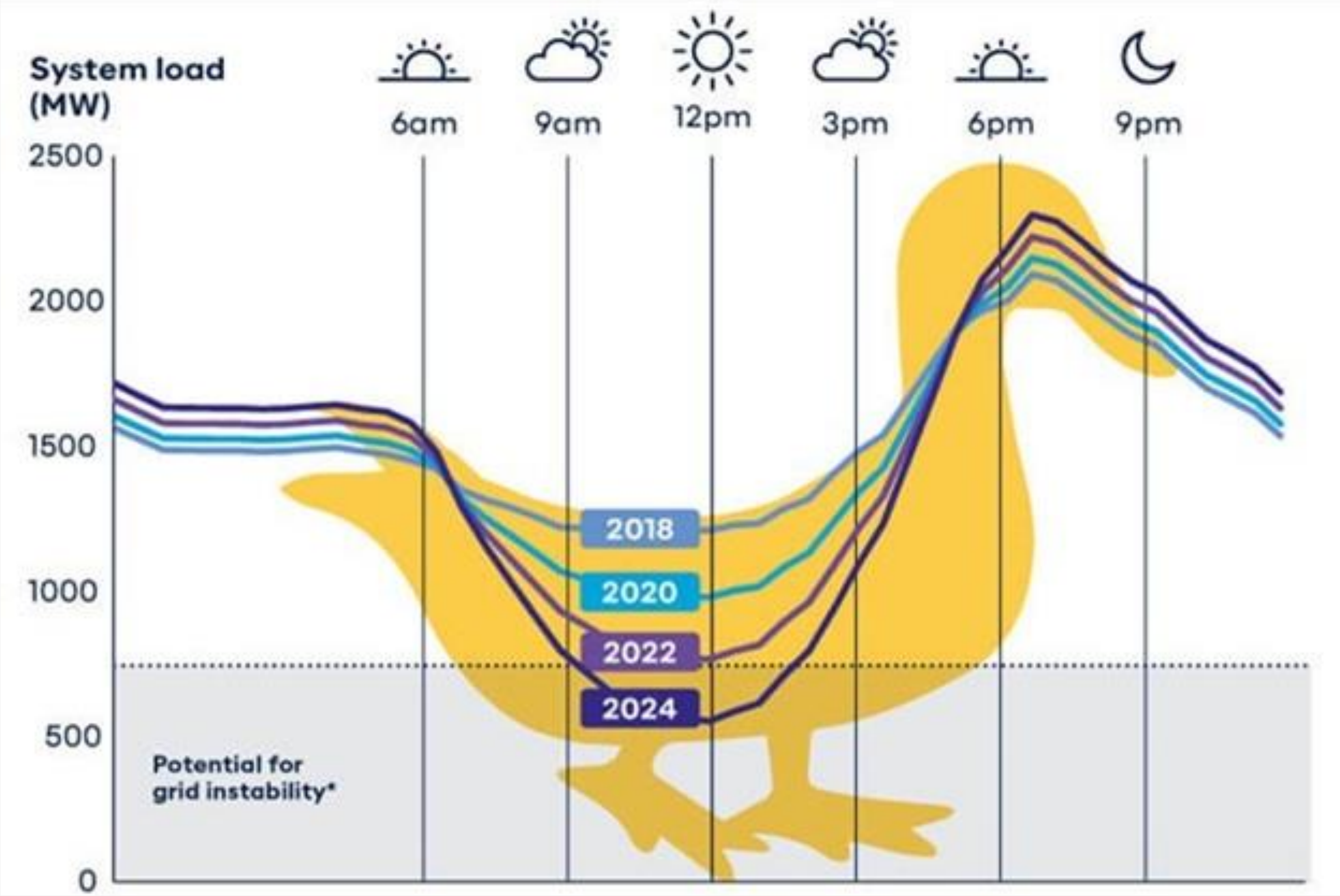
- How does EV charging affect electricity production?
- What is the cost to charge EVs?
- What are the CO_2 emissions of EVs charged from the grid?
- How do charging strategies affect the value story for EVs?

Unregulated charging



- “Uncontrollable” charging increases peak load
- Most expensive peaking generation is dispatched
- Implications for operating costs and adequacy of generation and T&D capacity

Effect of PV generation and EV charging on the Duck curve



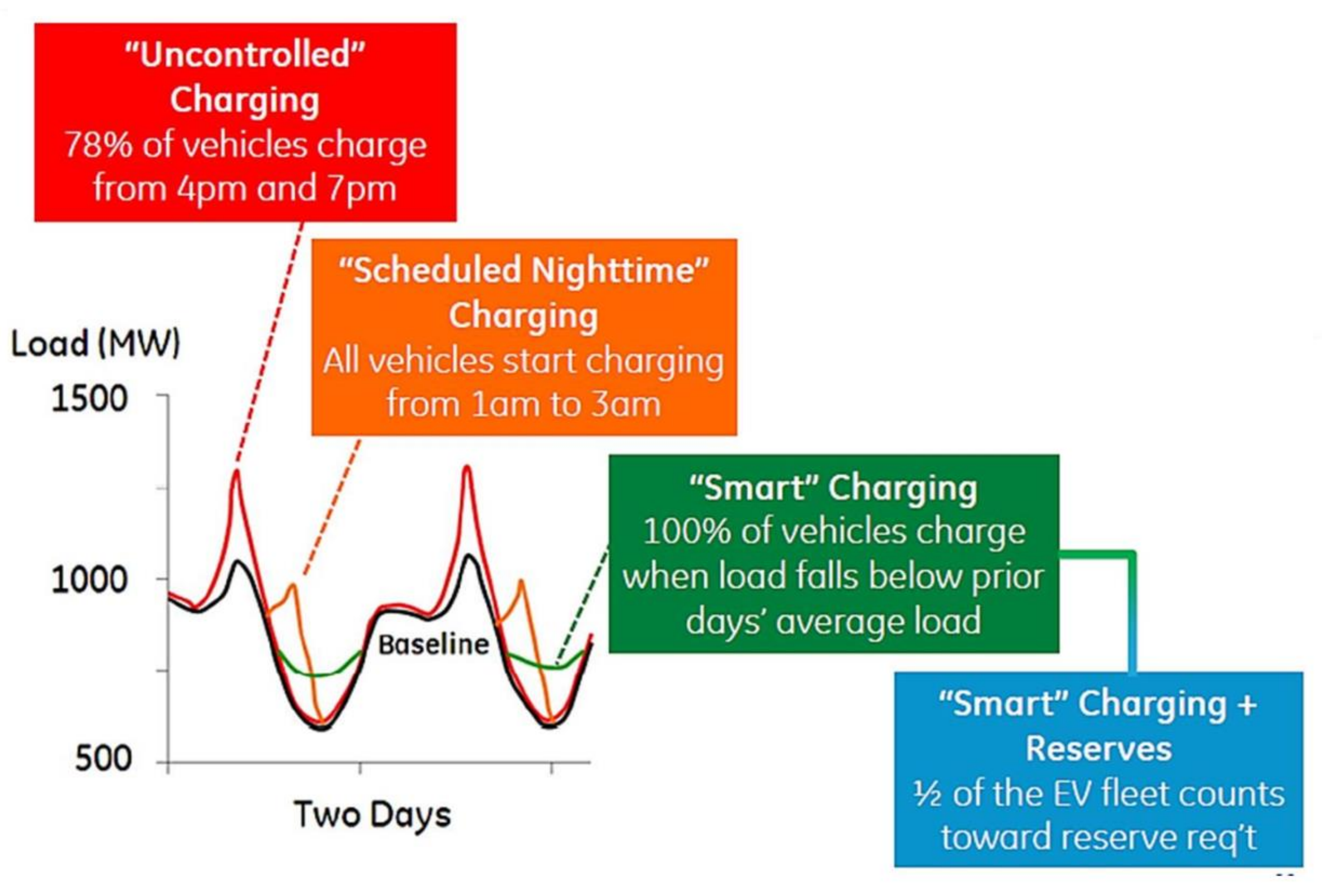
How EV charging affects the electricity grid

- Voltage stability issues
- Phase unbalance
- Supply and demand balance
- Overloading of power distribution components
- Power losses
- Frequency disturbance
- Harmonic distortions

Rate programs

- Interruptible rate
- Critical peak pricing rate
- Time of use rate
- EV TOU charging rate

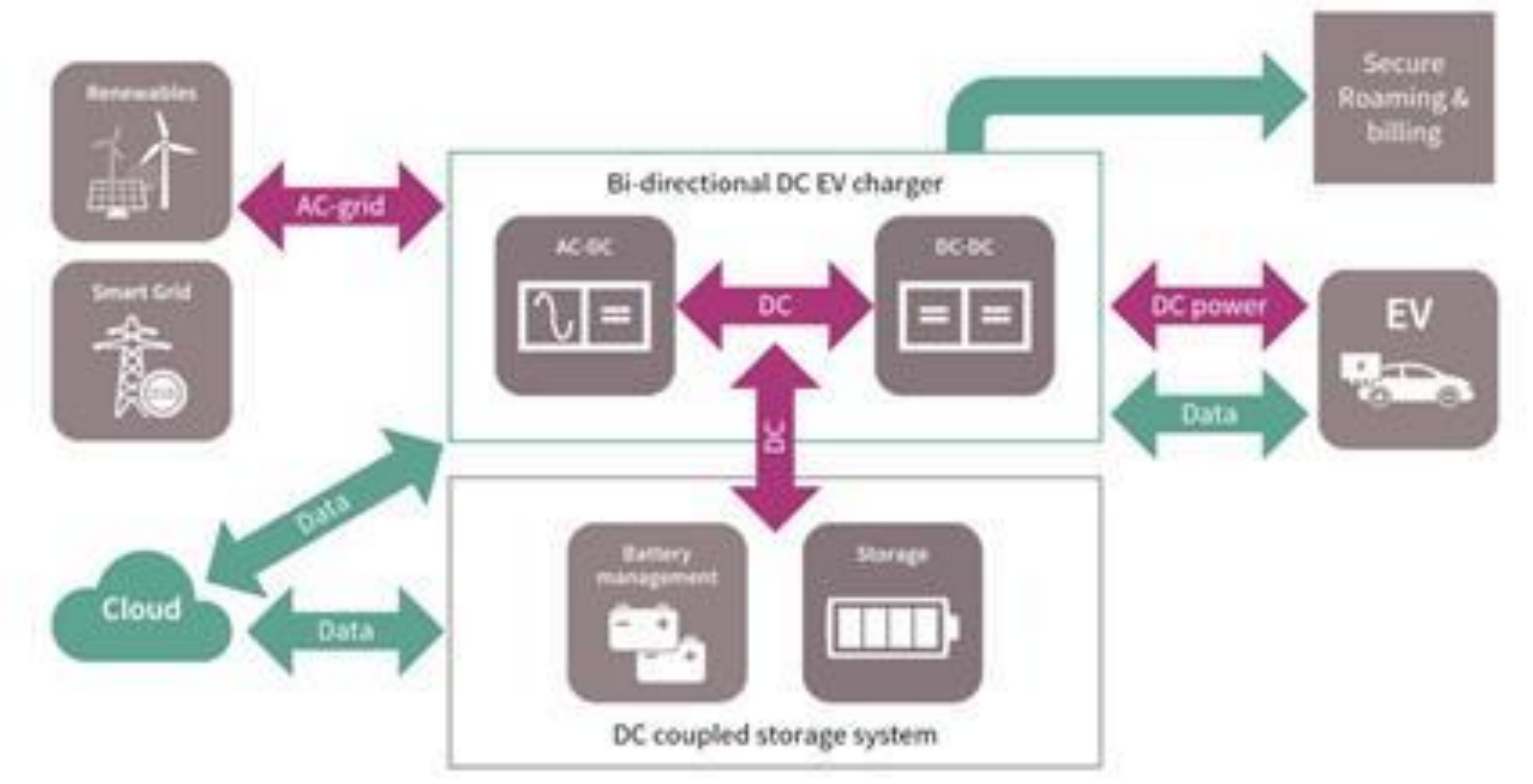
Smart charging



Mitigating EV charging impacts on power grid

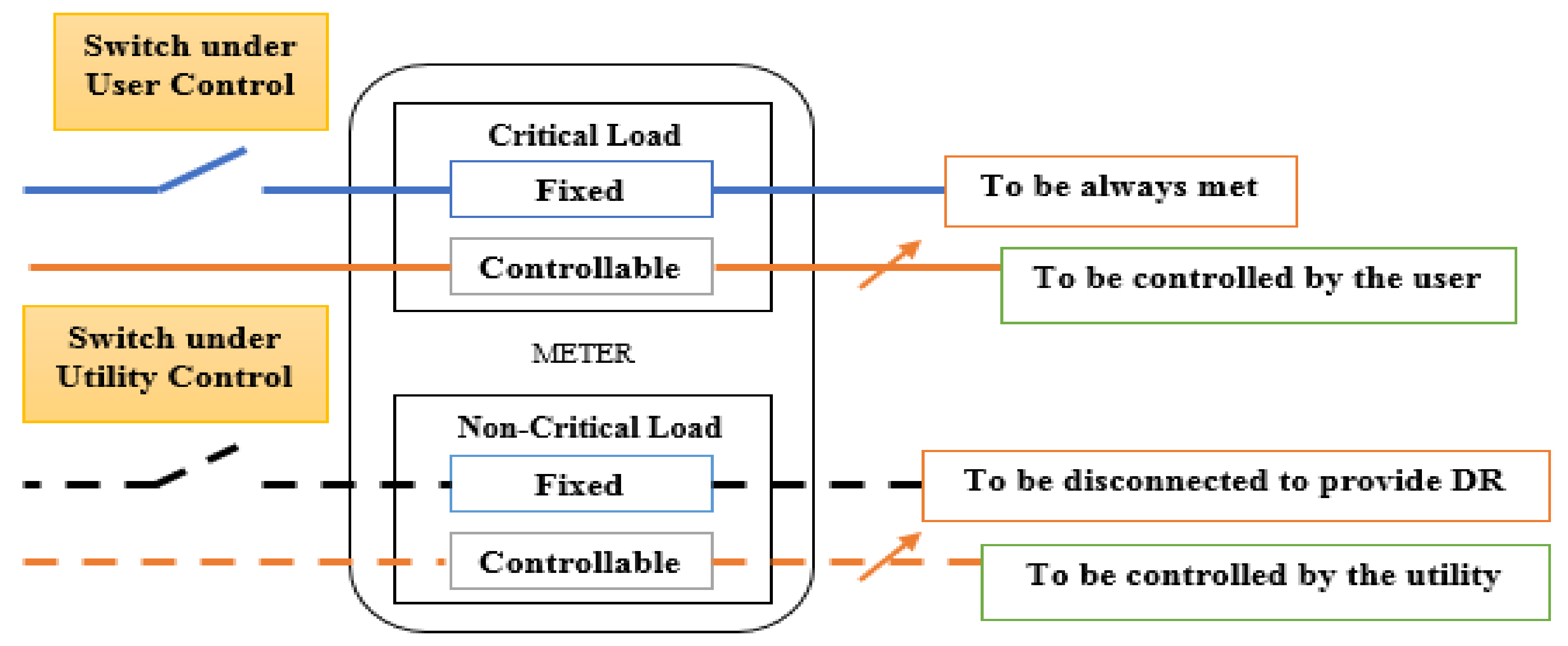
- Smart charging infrastructure: Smart charging algorithms leverage real-time data and dynamic decision-making to optimize the EV charging process.
- Vehicle-to-grid (V2G) integration: Vehicle-to-Grid (V2G) integration in EV charging is a transformative concept beyond the conventional charging paradigm.
- Renewable energy integration: Integrating renewable energy sources into EV charging systems provides a promising solution for enhancing grid stability and sustainability.

Mitigating EV charging impacts on power grid



Demand Response

Demand response



- Utility to ensure high reliable power for the critical loads … User to control.
- Utility to regulate non-critical loads … shed the fixed non-critical and control/shed non-critical loads.

Summary

- Distribution networks experience significant voltage variations due to Distributed Energy Sources (DER).
- Distribution networks’ SCADA systems need to be strengthened to increase availability, faster restoration of system, etc.
- New technology adoption like IOT applications, energy storage, etc. would improve integration of higher renewables.
- New grid friendly programs like AMI, demand response, etc. need to implemented.
- Addition of new loads should be done to develop a flat load curve.
- Load and RE forecasting should be carried out using innovative tools.
- EV charging philosophy needs to be developed/implemented.

Questions?

Economic and Social Commission for Western Asia

Integration Costs of Wind and Solar Power

Impact of RE on Grid Operation and Planning Aspects

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Wind/Solar Forecasting and Role of Renewable Energy Management Center(REMC)

Forecasting

Advantages

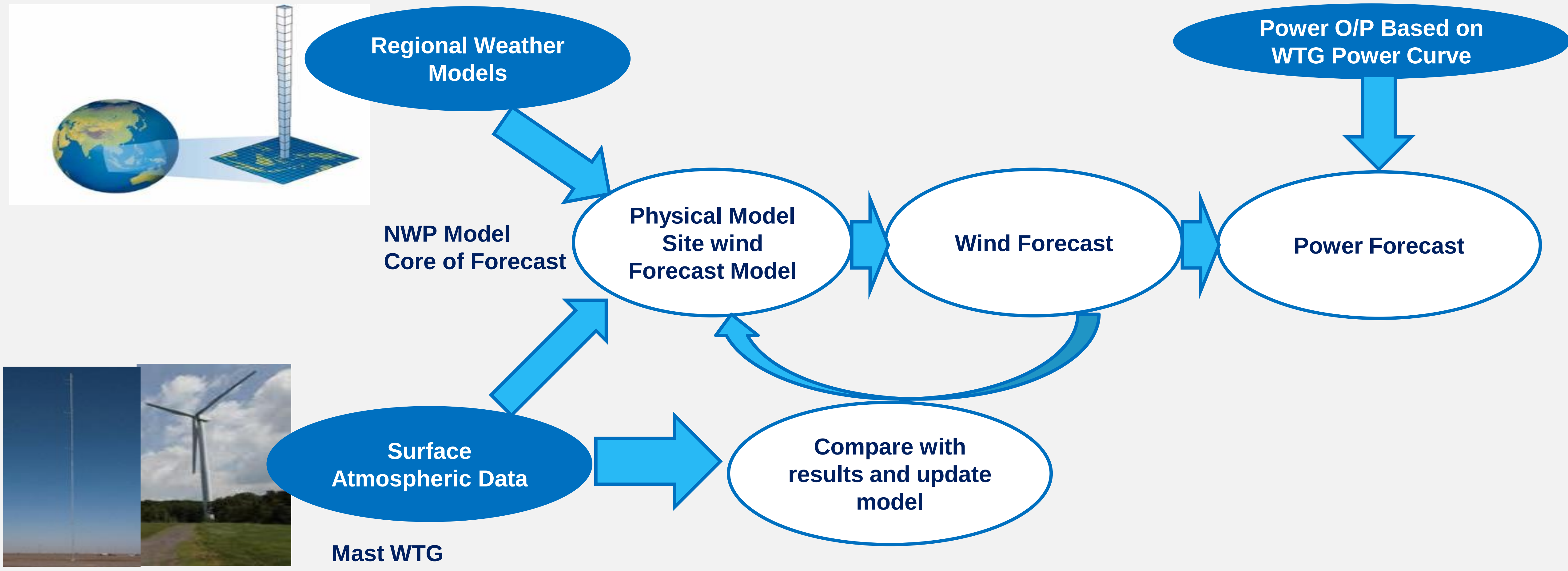
- Improves energy cost through better dispatch
- Helps in integration of larger quantities of wind generation in the grid

Challenges

- Existing EMS algorithms do not take into account wind uncertainties
- EMS systems do not have potential to exercise dispatch control of wind generation

Forecasting error should be managed through primary reserve

Wind forecasting approach



Regional Weather Models

Power O/P Based on WTG Power Curve

NWP Model
Core of Forecast

Physical Model
Site wind
Forecast Model

Wind Forecast

Power Forecast

Surface Atmospheric Data

Compare with results and update model

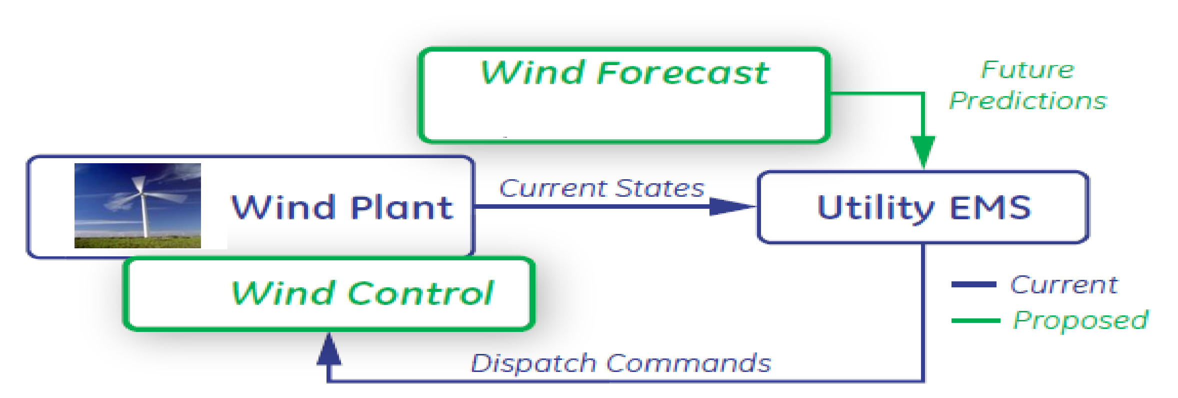
Mast WTG

Forecasting

An approach

- Need to build an EMS system with a grid model, wind power forecast model, wind plant simulator with SCADA and plant controls.

- Include advanced commitment and dispatch algorithms for wind plants in EMS



Ensure dispatchability and reduce curtailment

REMC

- RE Management Centre (REMC) were conceptualized for RE forecasting for long-term planning, operations and reserves management.
- REMCs are operational in countries like Spain, Germany, US, Denmark, India, Belgium and Australia.
- The REMCs use SCADA systems, forecasting and scheduling tools, visualization tools, display unit, and corresponding hardware and software, etc.
- They receive inputs from multiple Forecasting Services Providers (FSPs) as well as weather department.
- Sophisticated statistical models convert these parameters to generate the expected power output. Over a period of time, these statistical models can be improved based on actual production data.
- The AI techniques that would also be used for predictions are Machine Learning (ML) algorithm and Deep Learning (DL).

Dispatch interval reduction

- RE and load forecasting should be carried out for every 15-minute time block.
- Some systems are getting close to 5-minute level.

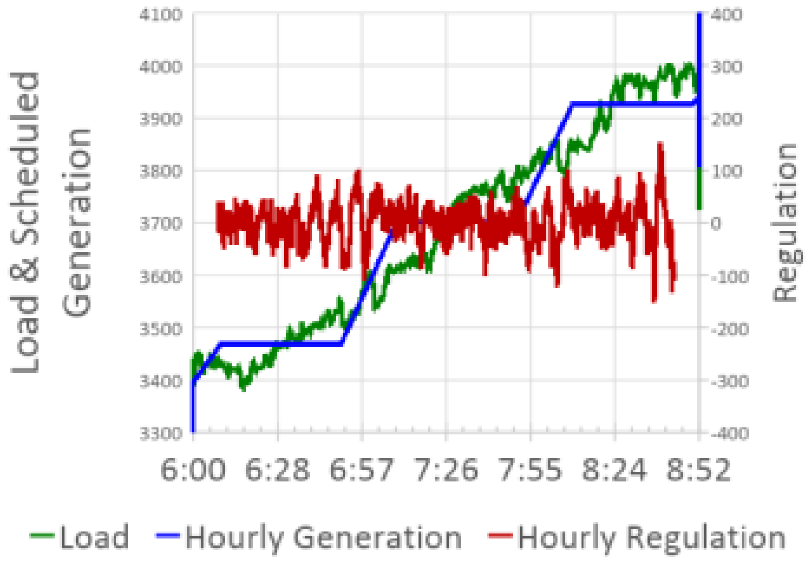


Figure. Hourly dispatch

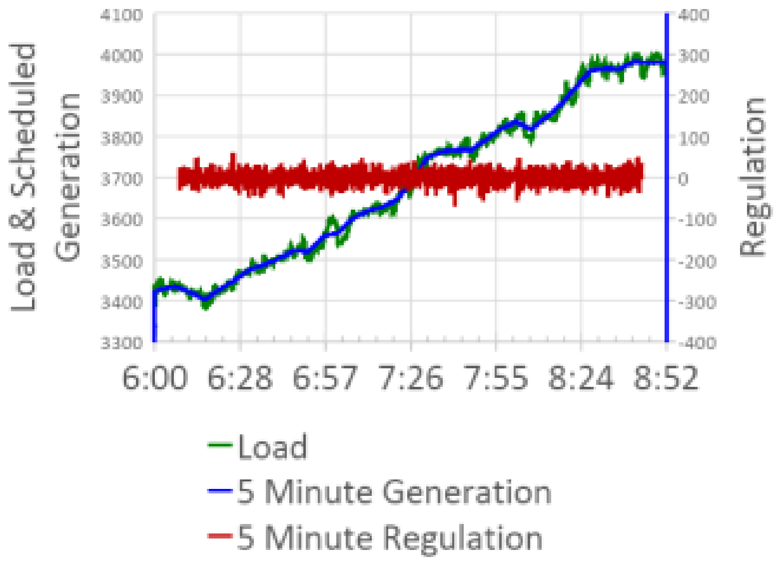
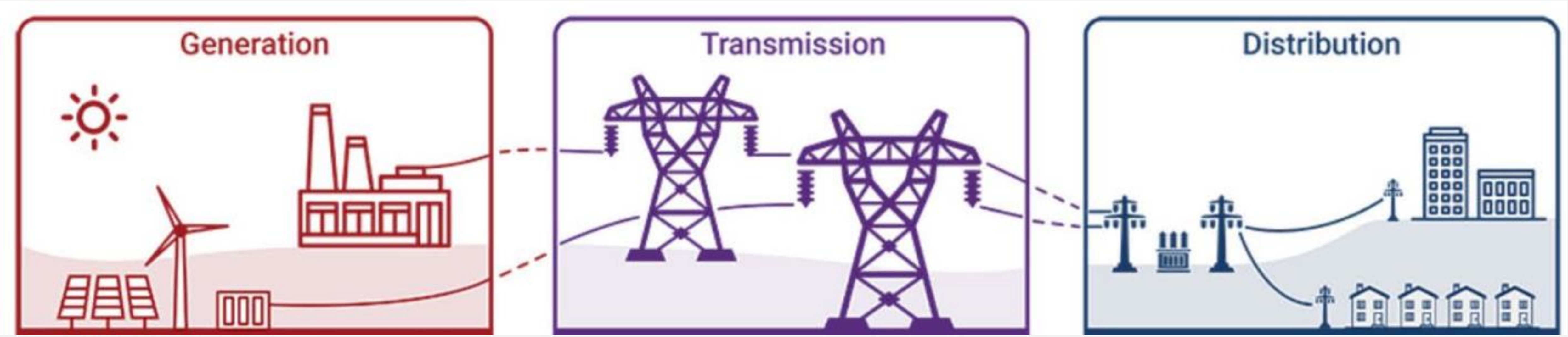


Figure. 5-minute dispatch

Role of Battery Energy Storage System (BESS)

Role of BESS

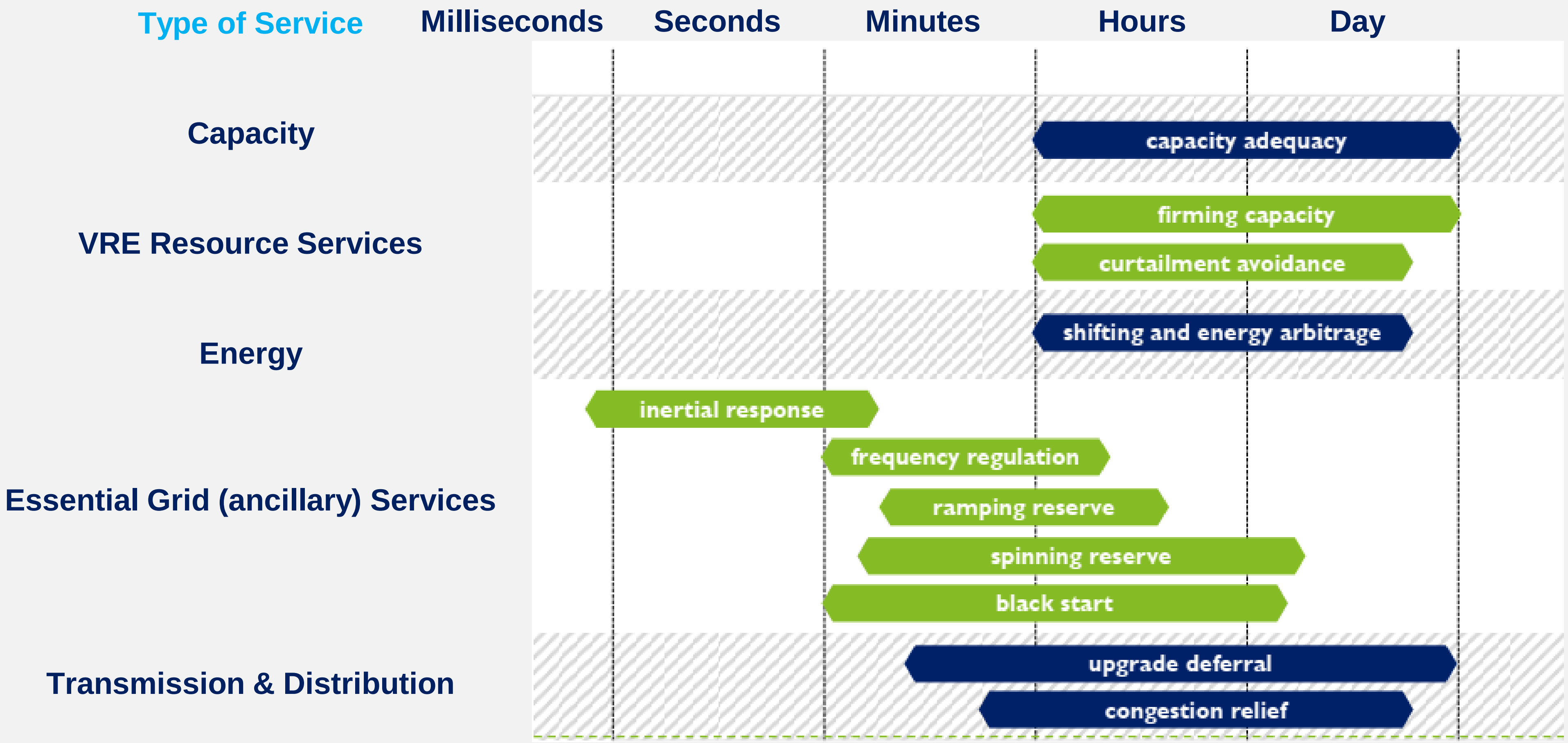


- Address supply disruptions
- Address variability of RE sources
- Provide peaking capacity

- Defer transmission upgrade
- Relieve transmission congestion
- Provide grid (ancillary) services

- Defer distribution upgrade
- Provide back-up power during outages
- Support microgrids

BESS applications



Type of Service

Milliseconds

Seconds

Minutes

Hours

Day

Capacity

capacity adequacy

VRE Resource Services

firming capacity

curtailment avoidance

Energy

shifting and energy arbitrage

Essential Grid (ancillary) Services

inertial response

frequency regulation

ramping reserve

spinning reserve

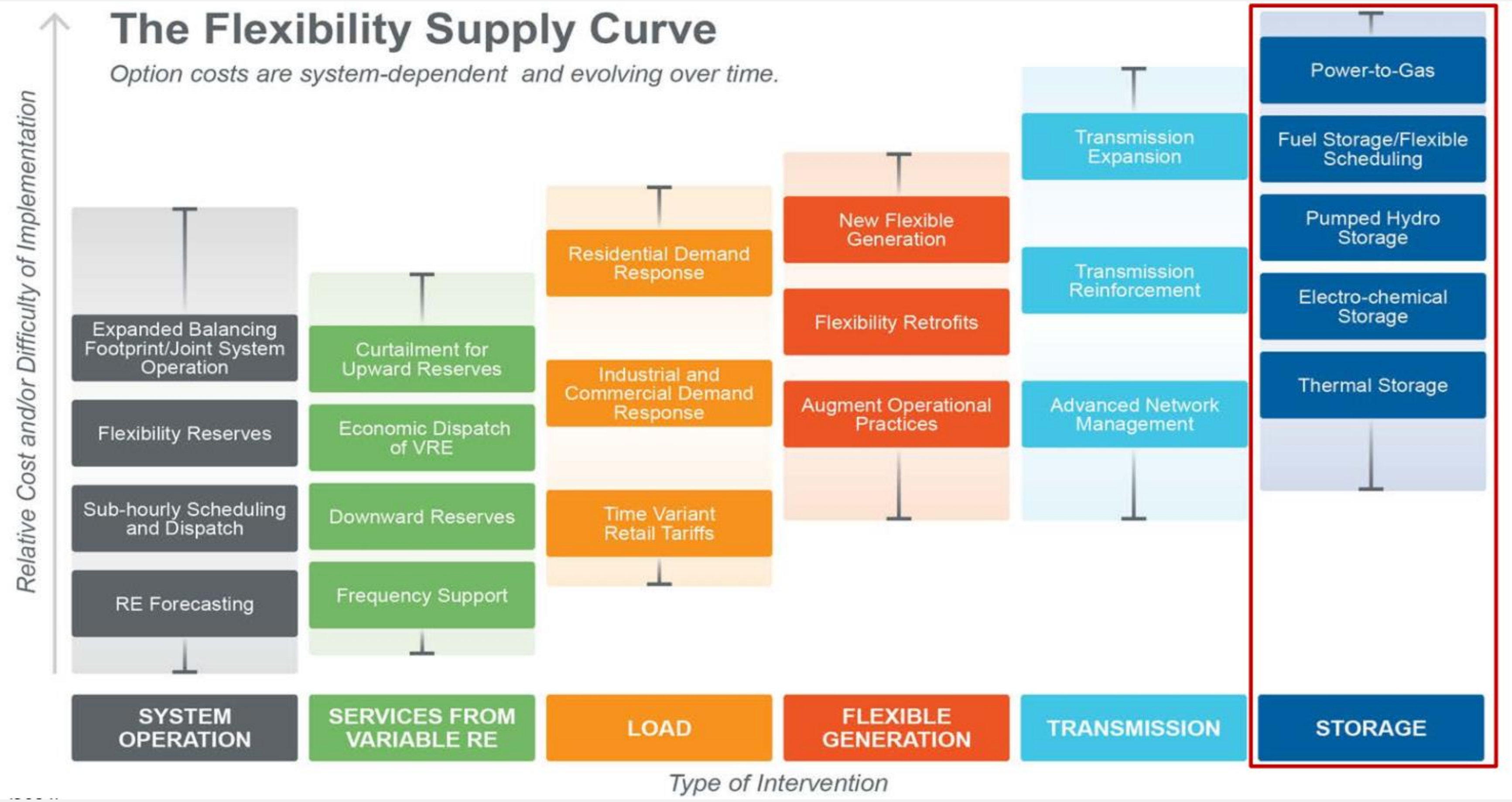
black start

Transmission & Distribution

upgrade deferral

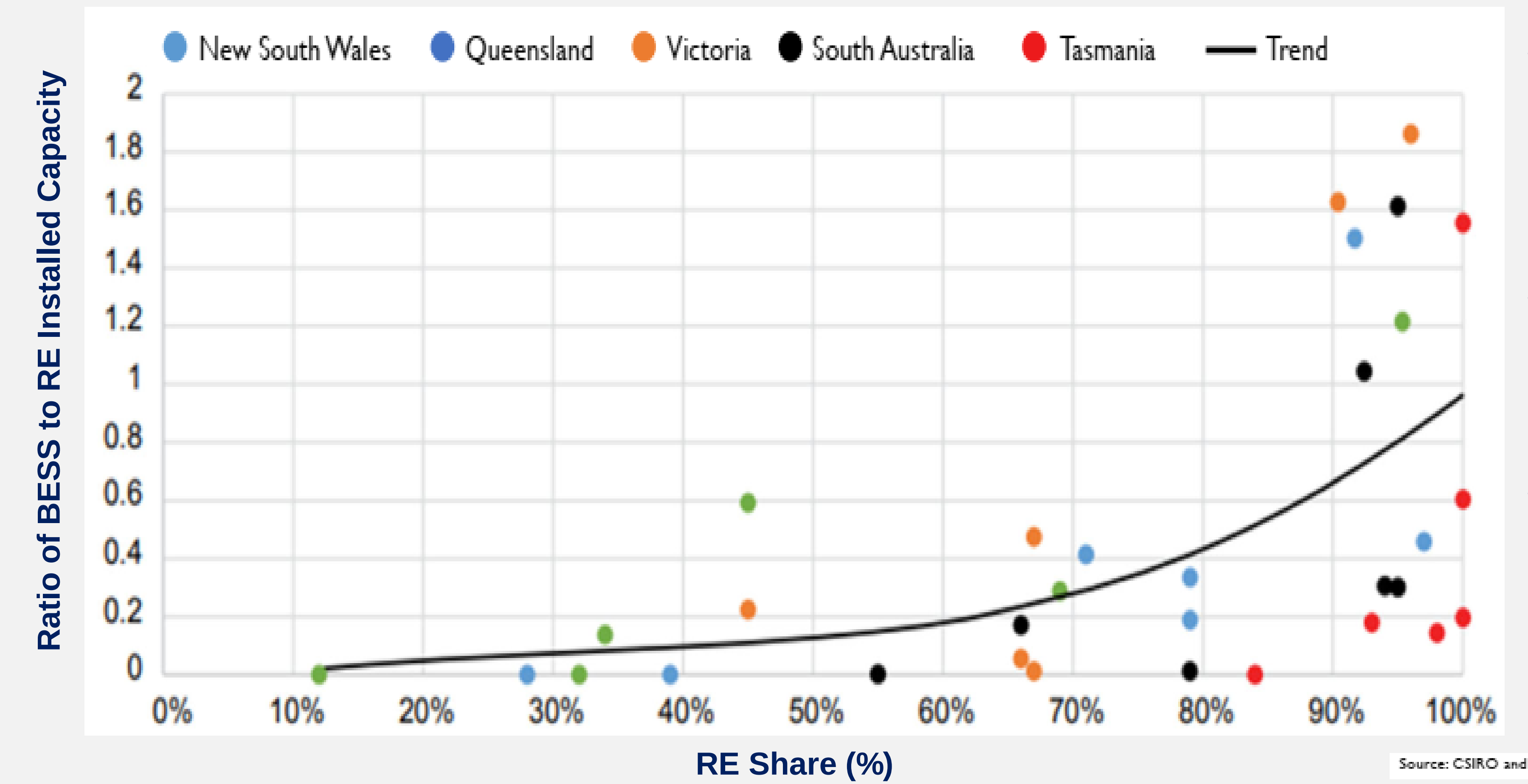
congestion relief

Role of energy storage



Source: Chernyakhovskiy et al. (2021)

How much BESS does the grid need?



Source: CSIRO and Energy Networks Australia, "Electricity Network Transformation Roadmap: Final Report," 2017

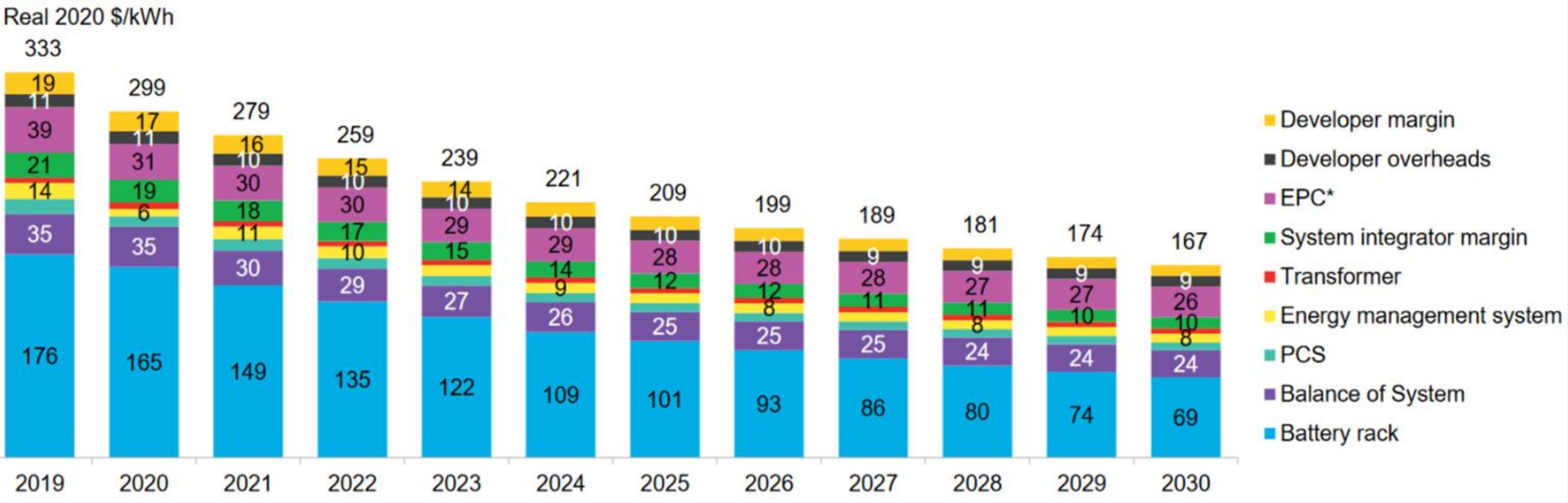
- Grids require a higher ratio of BESS to variable RE as more RE is deployed.

USA

- California may need 0.6 MW of storage for every 1 MW of renewables.
- New York may need 0.5 MW of storage for every 1 MW of renewables.

BESS price projection

Stationary storage system (4-hour AC battery energy storage system) cost trend, 2019-2030



Source: Bloomberg New Energy Finance (2022)

Development of Grid Codes and Validation

Grid codes

Initial Grid Code

- Safety, stability, and reliability.
- Frequency control, voltage regulation, and grid protection.

Grid Connectivity Standards

- Ensure that power plants, transmission lines, and distribution networks adhere to uniform technical specifications.

Frequency Control and Grid Stability

- More stringent requirements for frequency control and grid stability due to fluctuating demand and the variable output of renewable energy sources.

Power Quality

- Higher Quality of supply parameters such as voltage regulation, harmonics control, and power factor correction.
- Aim to enhance the reliability and efficiency of electricity supply to consumers.

Renewable Energy Grid Codes

- Revisions to the grid codes to accommodate the intermittent nature of RE sources.
- New technical standards to ensure smooth integration of RE (grid-friendly features) while maintaining grid stability.

Smart Grid Integration

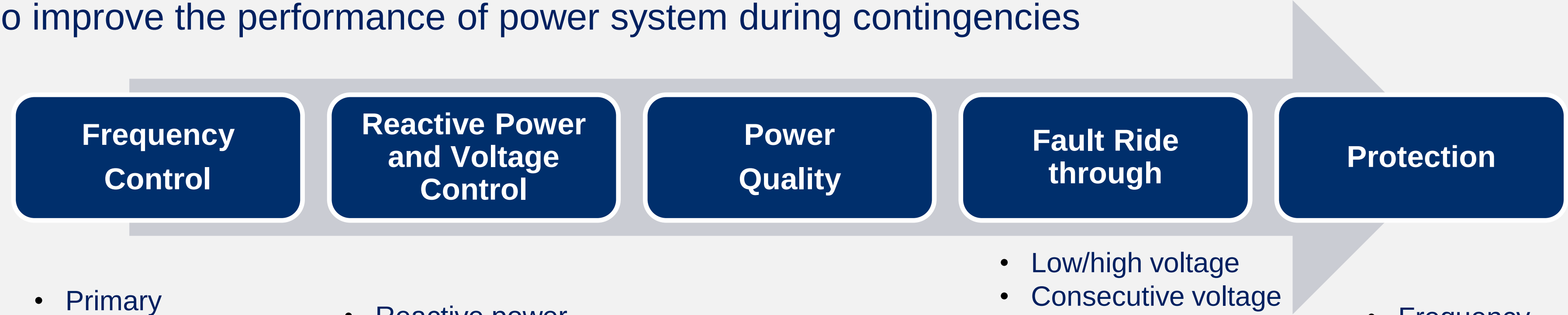
- Grid codes to be revised to incorporate advanced metering, grid automation, demand response, and distributed energy resources.

Grid Code Amendments and International Standards

- Reflect technological advancements, industry best practices, and changing energy landscape
- Align the grid codes with international standards and best practices to facilitate cross-border power exchanges

Grid code validation - IEEE 2800

- To improve the accuracy of power system study
  - Design data may be typical and have wide range of normal variation
  - Periodic retuning of controller settings
  - Retrofits with newer digital control
- To improve the performance of power system during contingencies



Frequency Control

- Primary Frequency Response
- Fast frequency response
- Rate of change of frequency (RoCoF)

Reactive Power and Voltage Control

- Reactive power capability
- Control modes: Voltage control, Power factor control and reactive power control modes

Power Quality

- Voltage fluctuations
- Voltage /current harmonic distortion
- Overvoltage contribution

Fault Ride through

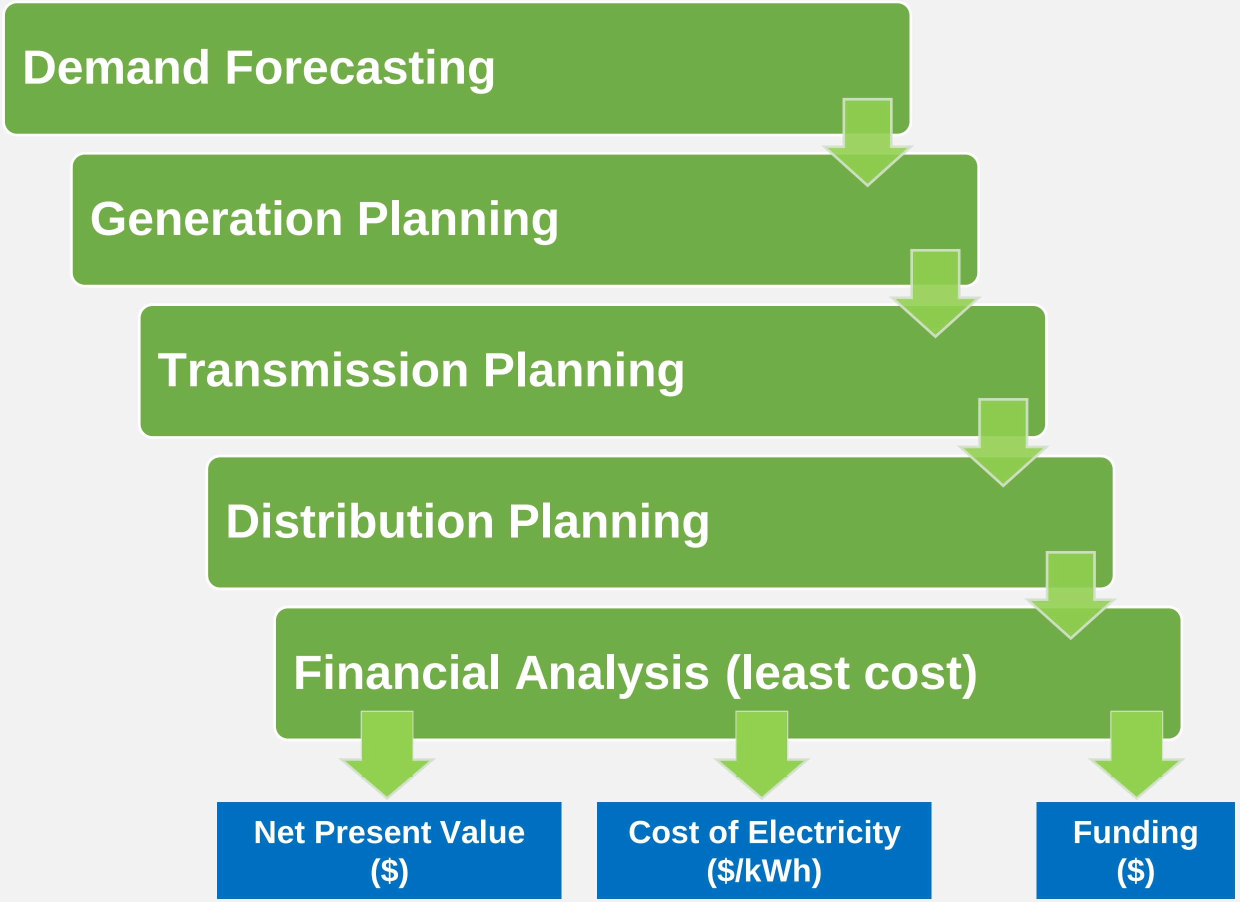
- Low/high voltage
- Consecutive voltage deviations
- Dynamic voltage support
- Transient over-voltages
- Low/High frequency
- RoCoF
- Voltage phase angle

Protection

- Frequency
- AC over-voltage/over-current
- Unintentional islanding
- Integrated protection

Planning Aspects

Utility planning



Demand Forecasting

Generation Planning

Transmission Planning

Distribution Planning

Financial Analysis (least cost)

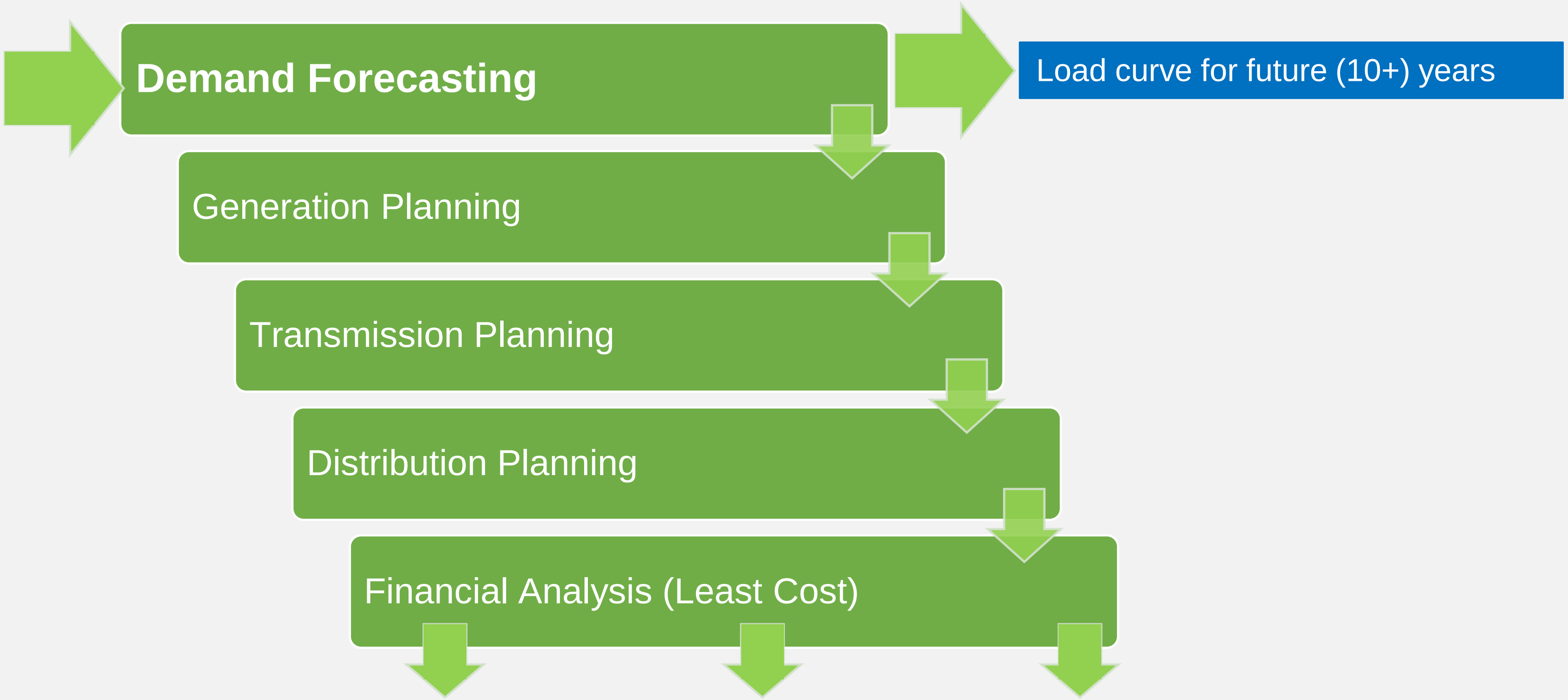
Net Present Value ($)

Cost of Electricity ($/kWh)

Funding ($)

Utility planning

Demand depends on:
1. Weather (Geography)
2. Historical trend
3. Economic trend
4. Export to other countries
5. Consider load shifting
   - Agricultural
   - Industrial
6. Integrate demand response
7. Include roof-top solar
8. Include energy efficiency programs



Demand Forecasting

Load curve for future (10+) years

Generation Planning

Transmission Planning

Distribution Planning

Financial Analysis (Least Cost)

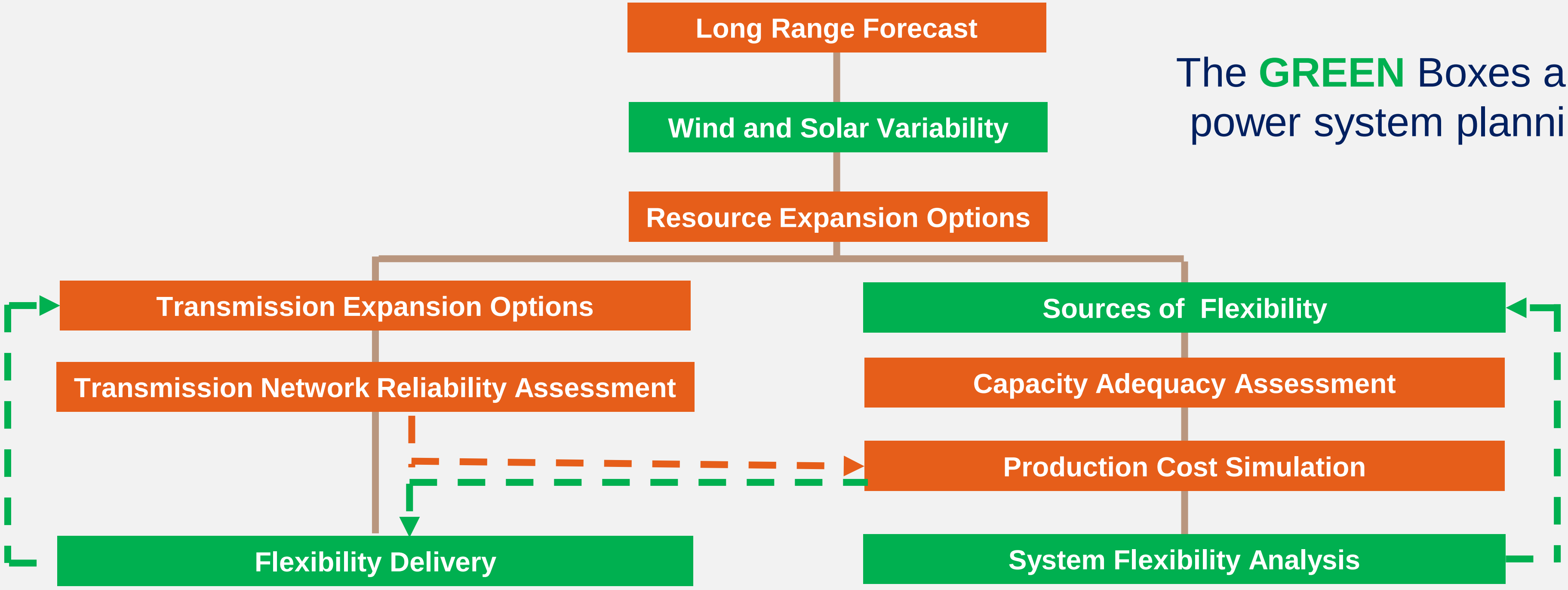
Tools: Statistical, ANN, etc.

Net Present Value ($)

Cost of Electricity ($/kWh)

Funding ($)

Changes in the planning



Long Range Forecast

Wind and Solar Variability

Resource Expansion Options

Transmission Expansion Options

Transmission Network Reliability Assessment

Flexibility Delivery

Sources of Flexibility

Capacity Adequacy Assessment

Production Cost Simulation

System Flexibility Analysis

The **GREEN** Boxes are the new Steps for power system planning with variable RE

Planning Decisions

Source: Milligan and Katz (2016)

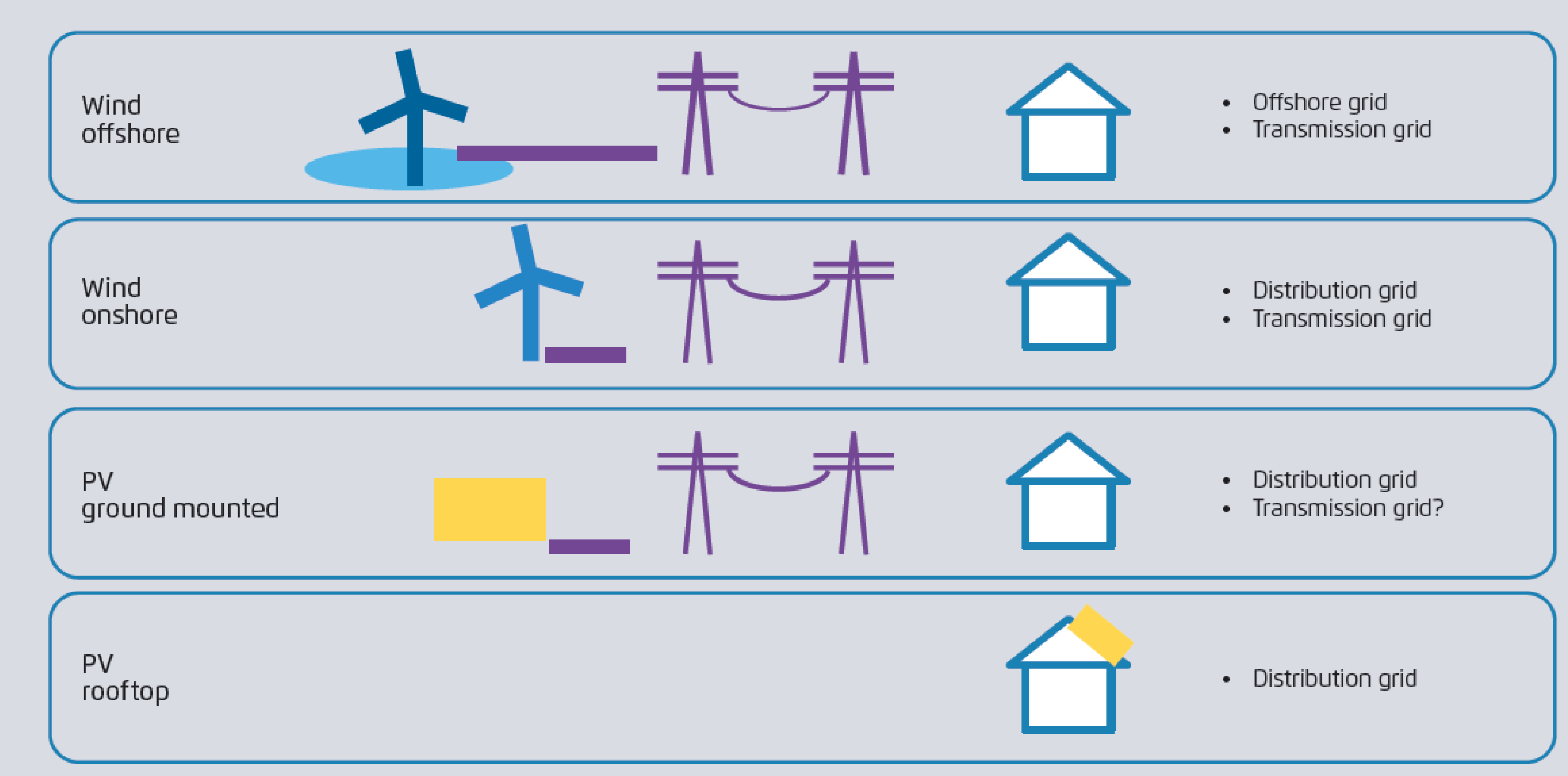
Grid and Balancing Costs

Grid Costs

Grid costs

- Grid costs include costs for transmission and distribution networks for new power plant.
- Grid costs include investment costs, power losses and certain ancillary services costs.
- Investment costs (capital costs) are often the largest component of grid costs.
  - These include the costs for building new or upgrading existing lines – overhead lines, underground cables, transformers and substations
  - Also include the costs of building voltage support equipment (e.g., FACTS devices)
- Losses that occur in the transport of power can contribute to grid costs for both distribution and transmission grids.

Grid costs for different types of RE technologies



- Grid costs depend on RE technologies.
- Offshore wind power requires a offshore grid as well as an onshore transmission network.
- Onshore wind farms and utility scale ground-mounted solar power plants are mostly connected to the transmission network.
- DER are connected to distribution network

Source: Agora Energiewende, 2015

Differences between RE and other technologies

- In principle, grid costs related to new wind and solar power plants are very similar to those related to the construction of any other type of power plant.
- Yet certain differences exist when adding wind and solar:
  - The connection is to the distribution grid not the transmission grid due to smaller average size of generating units (typically 0.1 to 100 MW as compared with >500 MW for conventional power plants).
  - The average utilization of connecting grids is lower due to the lower average utilization factor of the generator (typically 10-45 % compared with 20-85 % for dispatchable generators).
  - Sites with the best resources may be located far away from demand and the process of selecting sites may not consider cost for power transport.

Challenges in quantifying grid costs

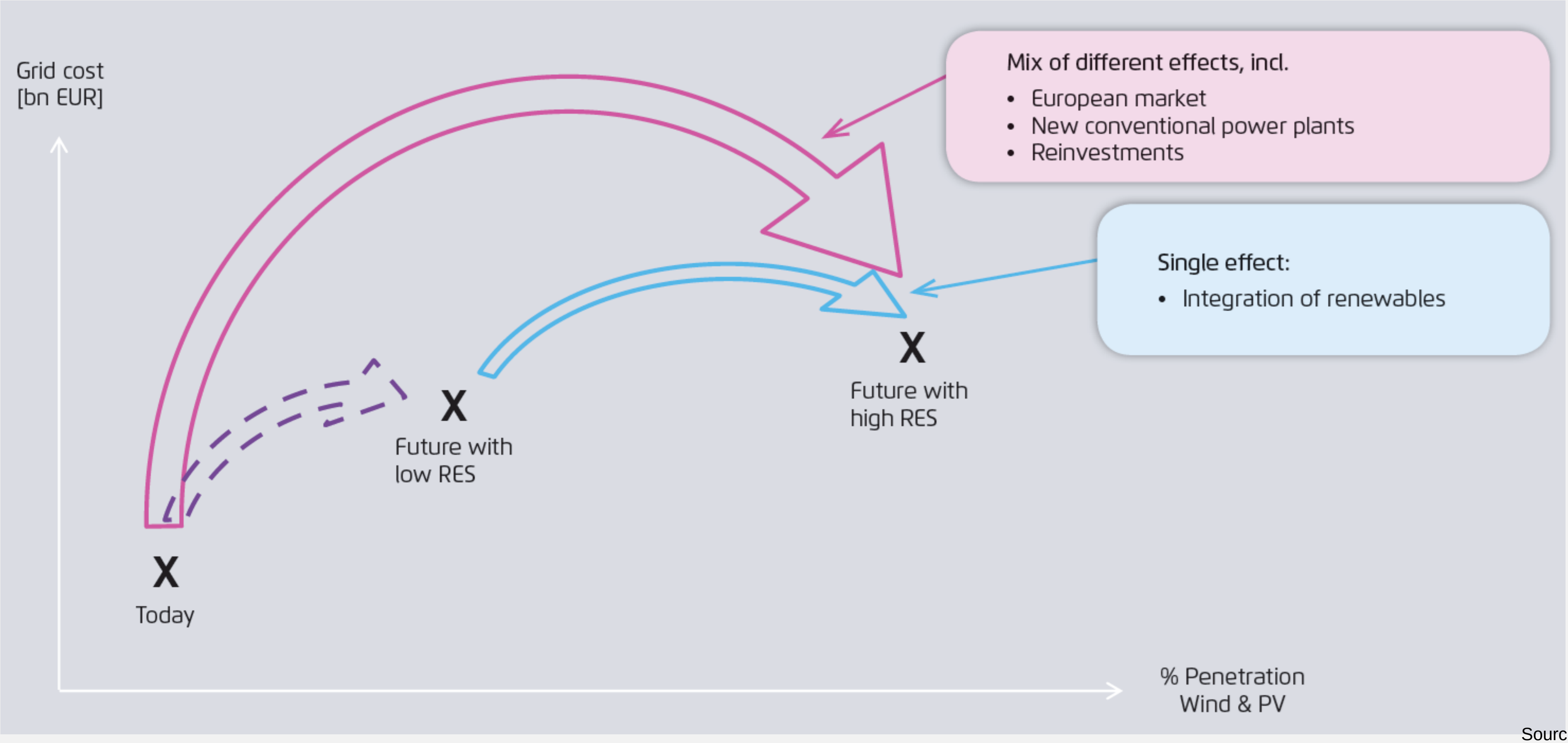
1. **Separating grid costs from other cost components**
   - Drawing a line between grid costs and other cost components is not always clear-cut, especially in three cases:
     - Curtailing peak in-feed of renewables can reduce grid costs but increase generation costs.
     - The costs of system services can be attributed to grid, balancing, or generation costs.
     - (Shallow) connection costs are sometimes count as grid costs, but often generation costs.

Challenges in quantifying grid costs

2. Extracting grid costs from scenarios

- Grid expansion studies typically estimate grid costs 10 to 20 years in the future.
- It would be wrong to attribute the entire increase in grid costs to renewable expansion.
- Other factors might drive grid costs as well, such as demand growth or a geographic shift of conventional capacity.
- Ideally, one would compare two future scenarios of the same year that differ only in the VRE penetration rate as represented in the next slide.
- When comparing grid costs between different years, many factors might have an impact on grid requirements and costs. For example, the nuclear phase-out in Germany increased the utilization of the transmission grid, as the southern part of the country was left with a larger electricity balance deficit.

Extracting grid costs from scenarios



Mix of different effects, incl.

- European market
- New conventional power plants
- Reinvestments

Single effect:

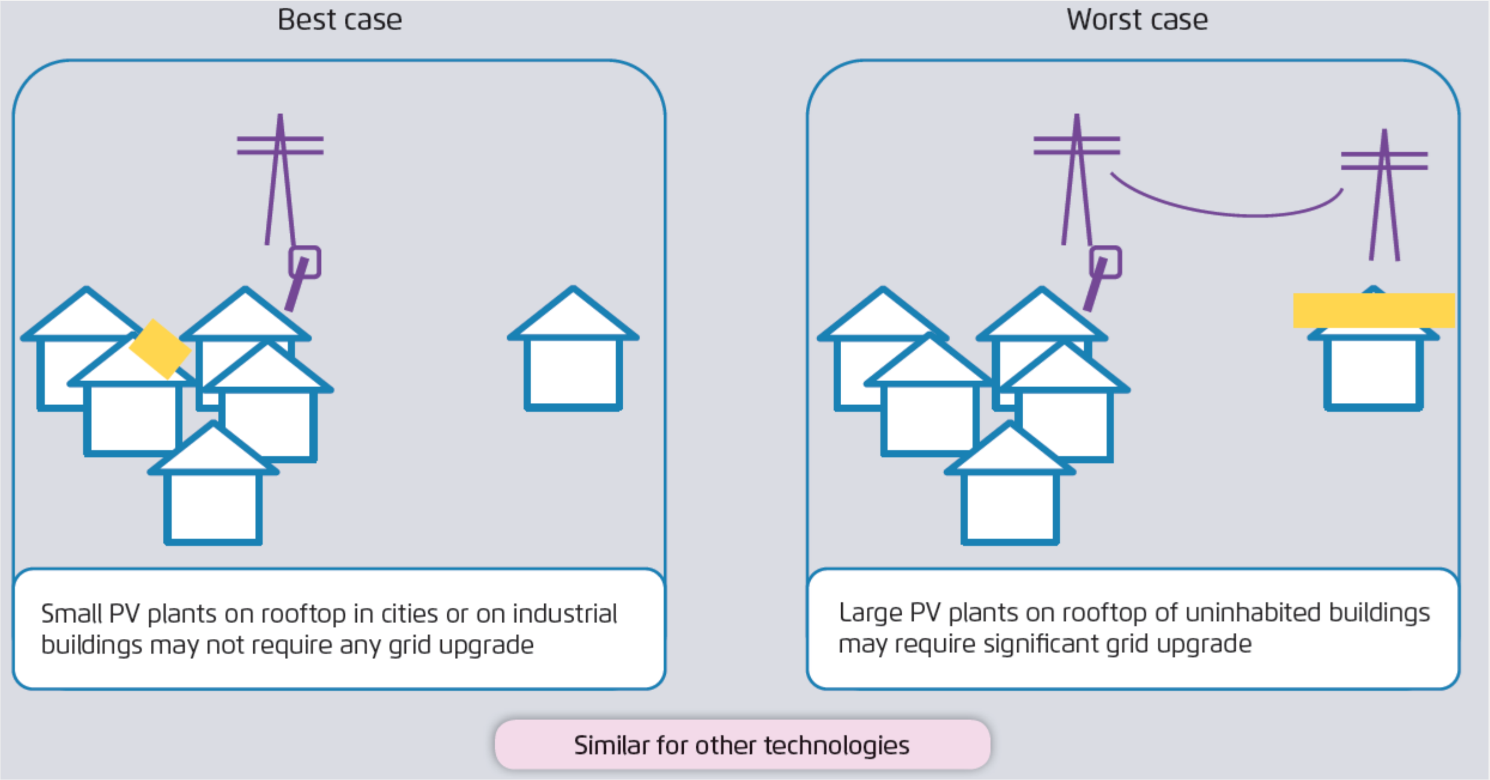
- Integration of renewables

Source: Agora Energiewende, 2015

Challenges in quantifying grid costs

3. Technology and case-specific grid costs

- Even within a single technology, grid costs can vary substantially, as can be shown using rooftop solar PV projects.



Small PV plants on rooftop in cities or on industrial buildings may not require any grid upgrade

Large PV plants on rooftop of uninhabited buildings may require significant grid upgrade

Similar for other technologies

Source: Agora Energiewende, 2015

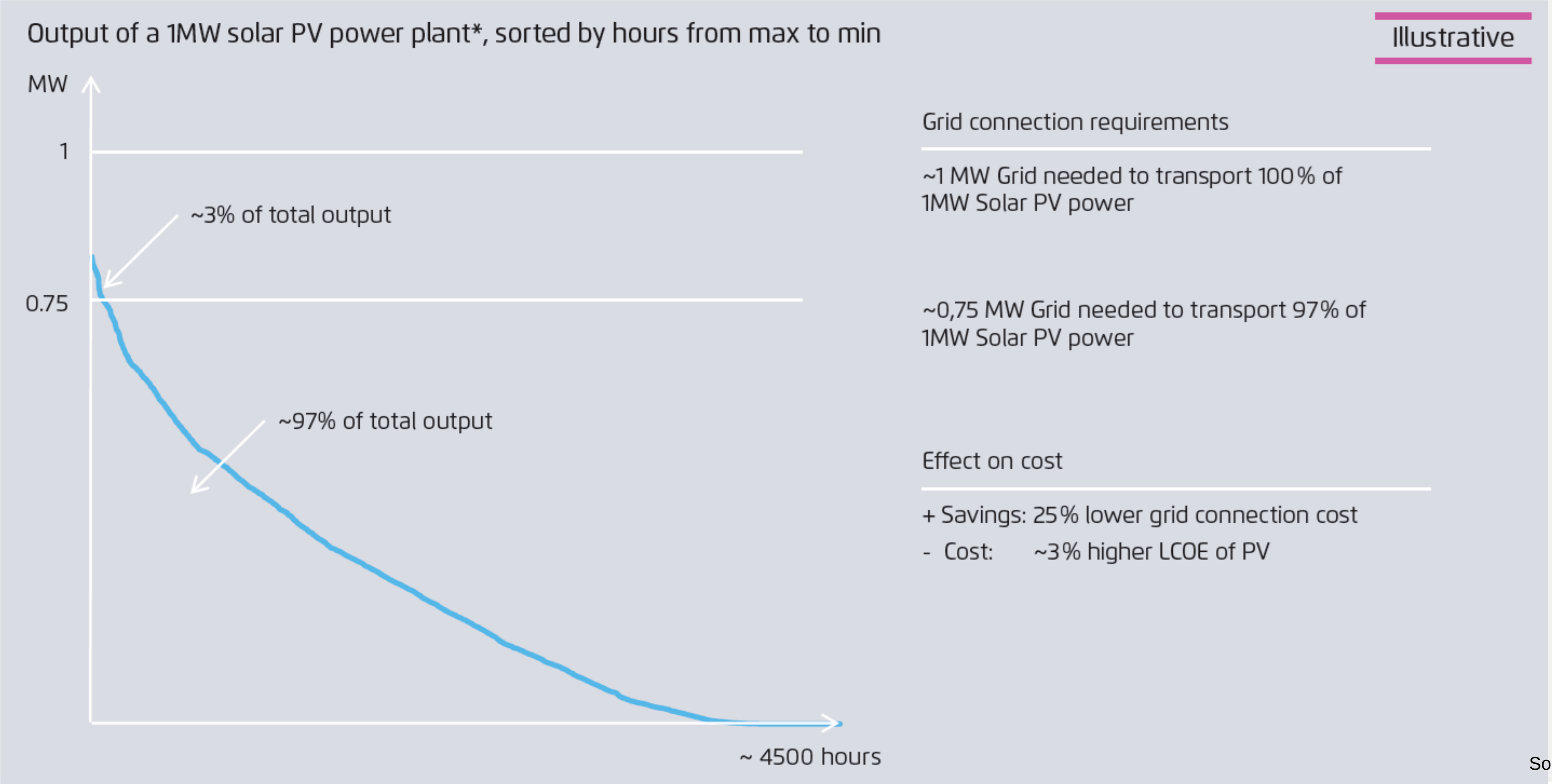
Challenges in quantifying grid costs

4. **New technologies and optimized planning approaches**
    - Many studies find that grid costs can be substantially reduced if innovative technologies, regulation or planning approaches are used.
    - Such “optimized” grid costs are often reported to be much lower than those under “business-as-usual” assumptions.
    - For example, flexible demand is frequently reported to have a major impact. So too is smart distribution grid equipment, transmission grid temperature monitoring, and the curtailing of in-feed peaks.
    - The degree to which studies account for these options affects cost estimates.

Options for limiting grid costs

- Grids that connect wind and solar PV power plants do not necessarily need to be designed to transport the maximum power output; no one could guarantee that the plant would produce at maximum output during the hour of highest demand.
- Their design may focus on transporting the power produced by wind and solar PV as cost effectively as possible.
- Cost optimal grid design for wind and solar PV power plants may look at the total cost of the generation and grid connection, and accept that a small share of (potential) generation is lost for the sake of lower grid cost.
- The following figure shows the effect of such an optimization based on the feed-in data of an individual solar power plant.

Cost effects of curtailing maximum in-feed of solar power


Output of a 1MW solar PV power plant*, sorted by hours from max to min

Illustrative

Grid connection requirements

~1 MW Grid needed to transport 100 % of 1MW Solar PV power

~0,75 MW Grid needed to transport 97% of 1MW Solar PV power

Effect on cost

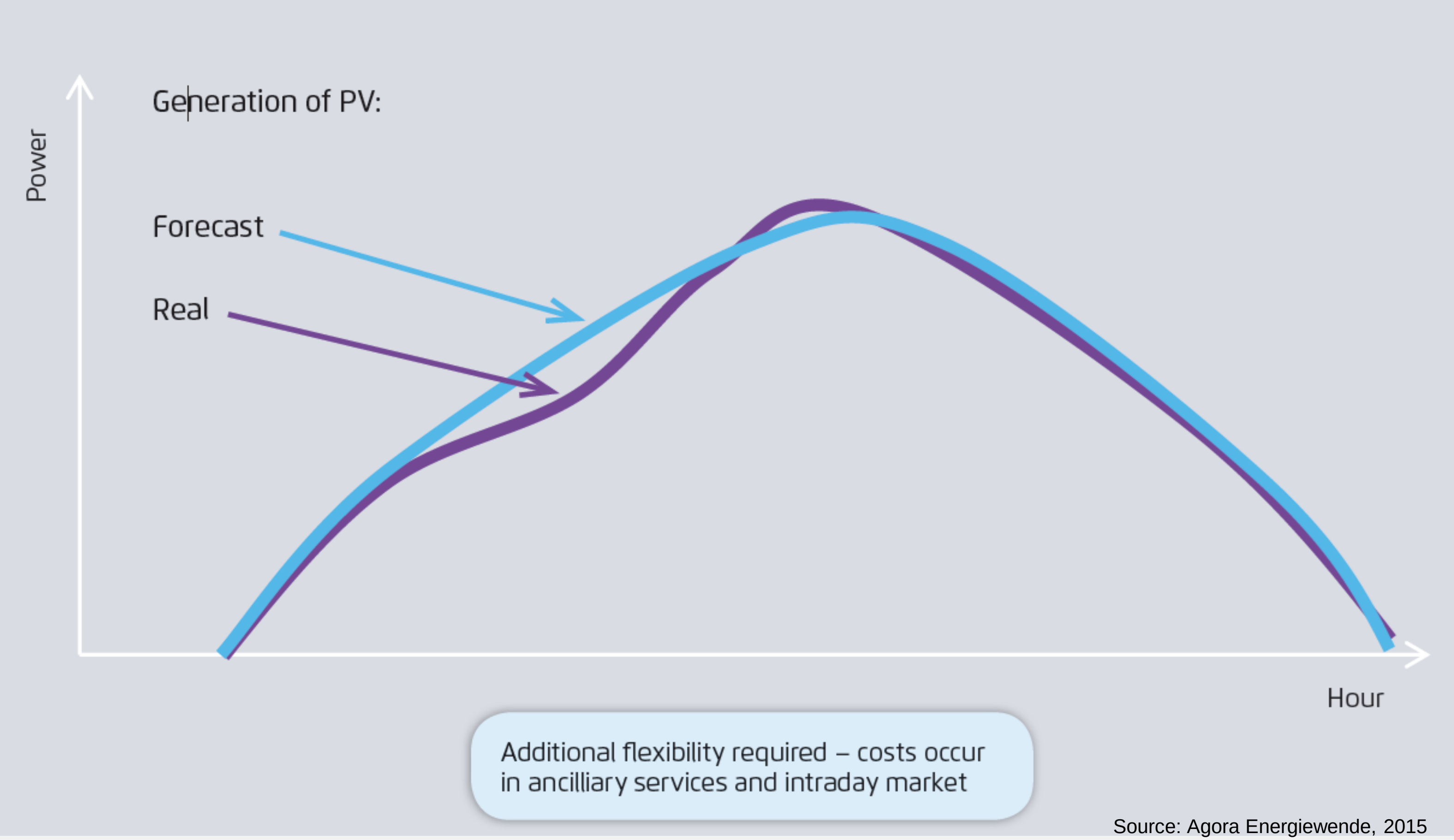
+ Savings: 25 % lower grid connection cost
- Cost: ~3 % higher LCOE of PV

Source: Agora Energiewende, 2015

Balancing costs

Balancing costs

- Balancing costs are the costs incurred in balancing deviations of actual generation from the forecasted generation.



Source: Agora Energiewende, 2015

Challenges in quantifying balancing costs

- Three major challenges exist when calculating balancing costs:
  - Some approaches include the costs of holding balancing reserves; others don’t.
  - Imbalance prices that generators pay today are often not cost reflective.
  - Studies vary in how they define “short-term” balancing.

- Most balancing power markets have two components: reservation of balancing reserves and activation of these reserves.

- Reserving capacity is often remunerated with a capacity price and activating capacity, with an energy price.

Options for limiting balancing costs

- A variety of options exist for reducing balancing costs. The options can be clustered into three groups:
  - Improving forecasts
  - Improving balancing markets and integration
  - Improving short-term spot markets

Improving forecasts

- Smaller wind and solar power forecast errors mean less balancing costs.
- Wind and solar power forecasting continues to improve and there is room left especially in short-term forecasting (few hours).
- The economic incentive for improving forecasts is the price paid for forecast errors which is known as the imbalance price. Therefore, the economic incentives need to be set right.

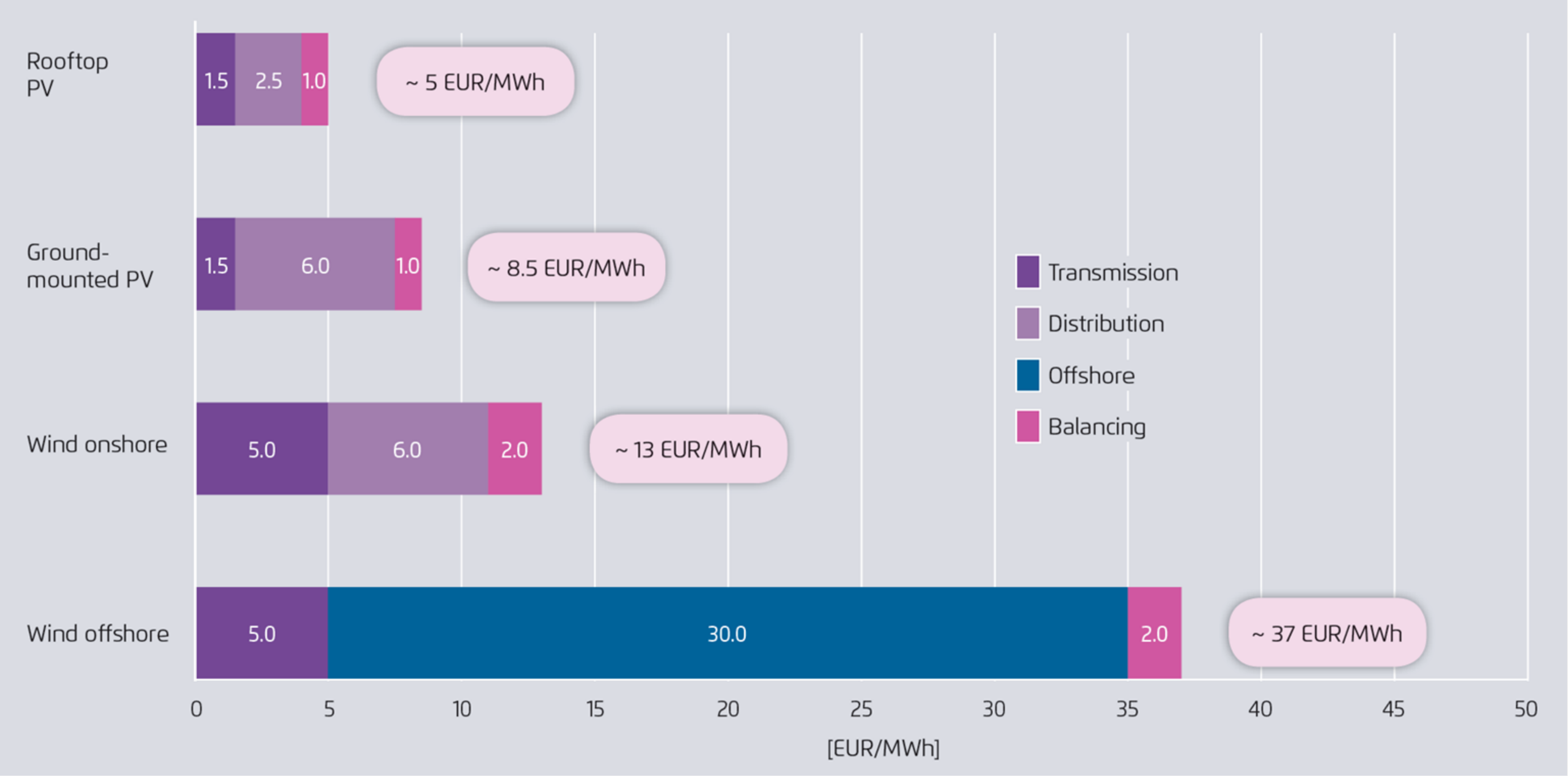
Improving balancing markets and integration

- The sizing of balancing reserves could be adjusted according to the current state of the power system.
- For example, if a wind front is expected to arrive the next day, additional reserves could be procured.
- Increased international cooperation among TSOs, such as imbalance netting, reduces balancing costs.
- Market design of balancing power markets could be adjusted so that more market participants could supply these services.
- Frequent auctions (daily) and short contract duration (1 hour) could enable balancing power to be provided not only from the demand side, but also from wind and solar power.
- The larger the balancing area, the more forecast errors from individual plants balance each other out.

Improving short-term spot markets

- More liquid intra-day spot markets with shorter gate-closure times and reduced trading intervals (15 minutes, say) help VRE generators manage forecast errors without relying on balancing systems.

Typical grid and balancing costs for RE



Source: Agora Energiewende, 2015

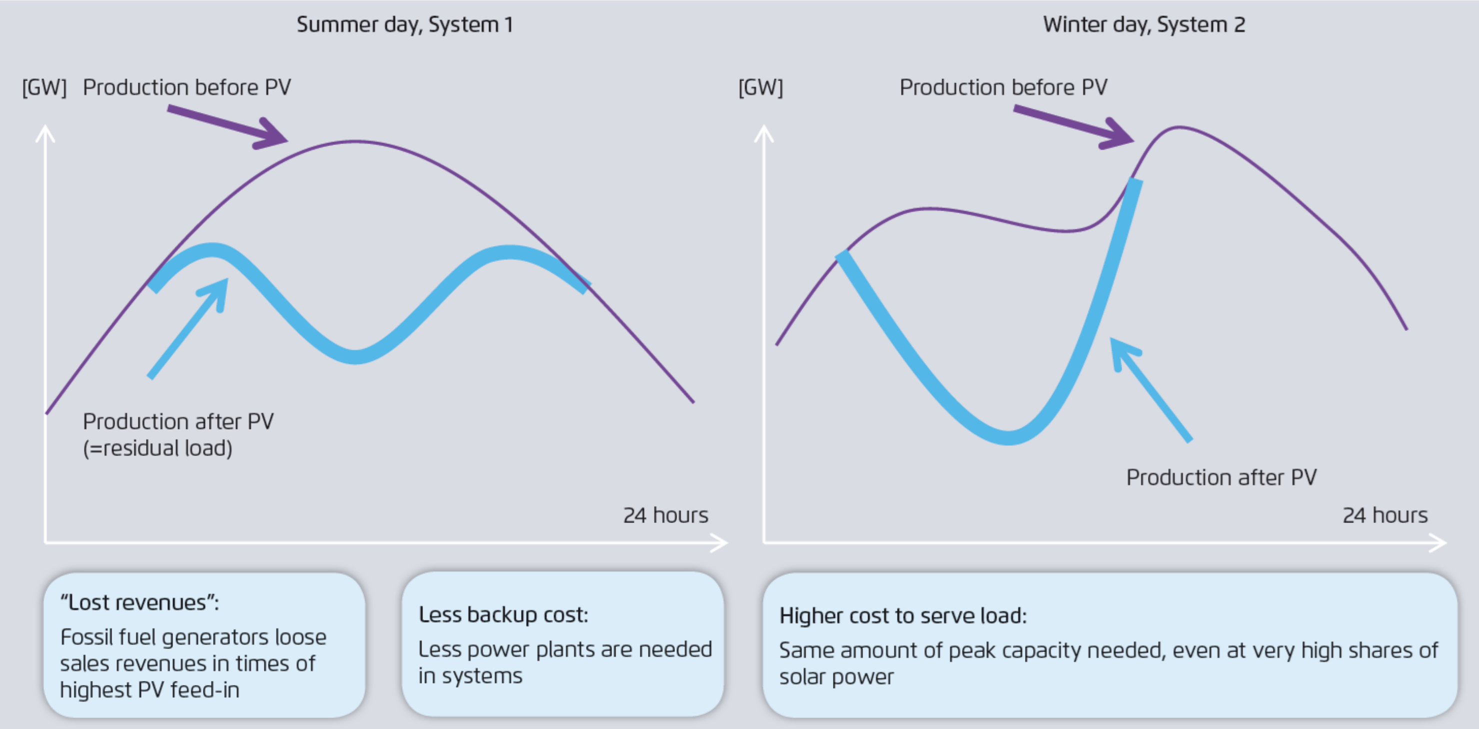
Costs (or benefits) from Interaction with Other Power Plants

Effects of VRE on existing power plant utilization

- Adding any type of new power plant reduces the utilization of existing power plants.
- It has been debated whether this effect can (and should) be considered as an integration cost and how the value of power plants and/or lost revenues of operators can be quantified.
- At high penetration rates, the effect from new wind and solar power plants may differ significantly from those of new baseload power plants.
- The former requires more dispatchable capacity in the system and a changed pattern of residual demand, leading to a shift of power production from base load to mid-merit and peak load power plants.

Effects of VRE on existing power plant utilization

The “best case” scenario



“Lost revenues”:
Fossil fuel generators loose sales revenues in times of highest PV feed-in

Less backup cost:
Less power plants are needed in systems

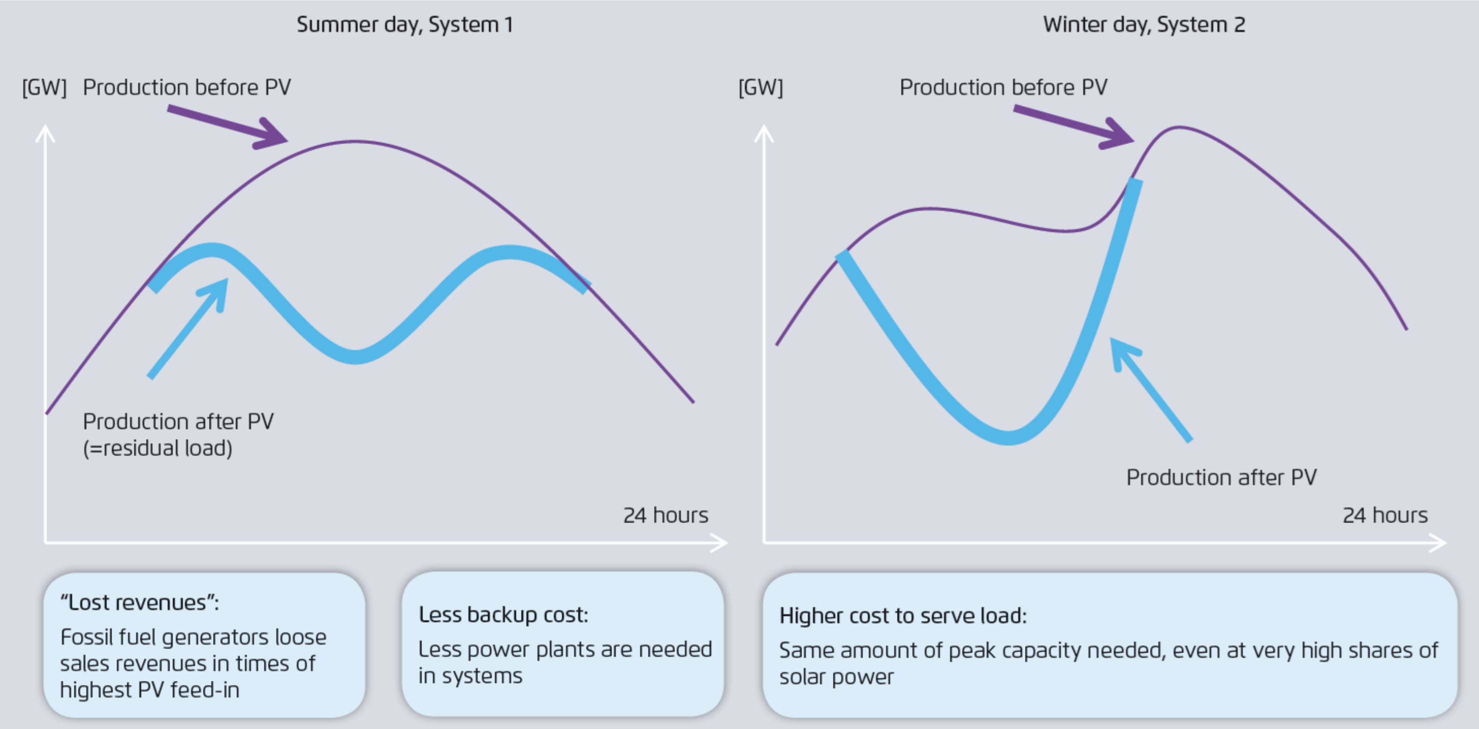
Higher cost to serve load:
Same amount of peak capacity needed, even at very high shares of solar power

- The best-case example (left) is a system with a strong correlation of solar irradiation and electricity demand, which may occur in countries with high demand for air conditioning.
- When adding solar PV to this system, less total installed thermal power plant capacity is required (assuming a constant demand) and generation by thermal power plants during peak loads – usually the most expensive electricity within a system – is reduced.

Source: Agora Energiewende, 2015

Effects of VRE on existing power plant utilization

The “worst case” scenario



“Lost revenues”:
Fossil fuel generators loose sales revenues in times of highest PV feed-in

Less backup cost:
Less power plants are needed in systems

Higher cost to serve load:
Same amount of peak capacity needed, even at very high shares of solar power

- The effect of adding solar PV in the worst-case example (right) is quite different.
- The highest demand occurs in the evening hours after sunset, which may arise in winter times in countries with a cold climate.
- Adding very high shares of solar PV would not help the system during the highest load.
- The total thermal power plant capacity required is the same as before solar PV.

Source: Agora Energiewende, 2015

Effects of VRE on existing power plant utilization

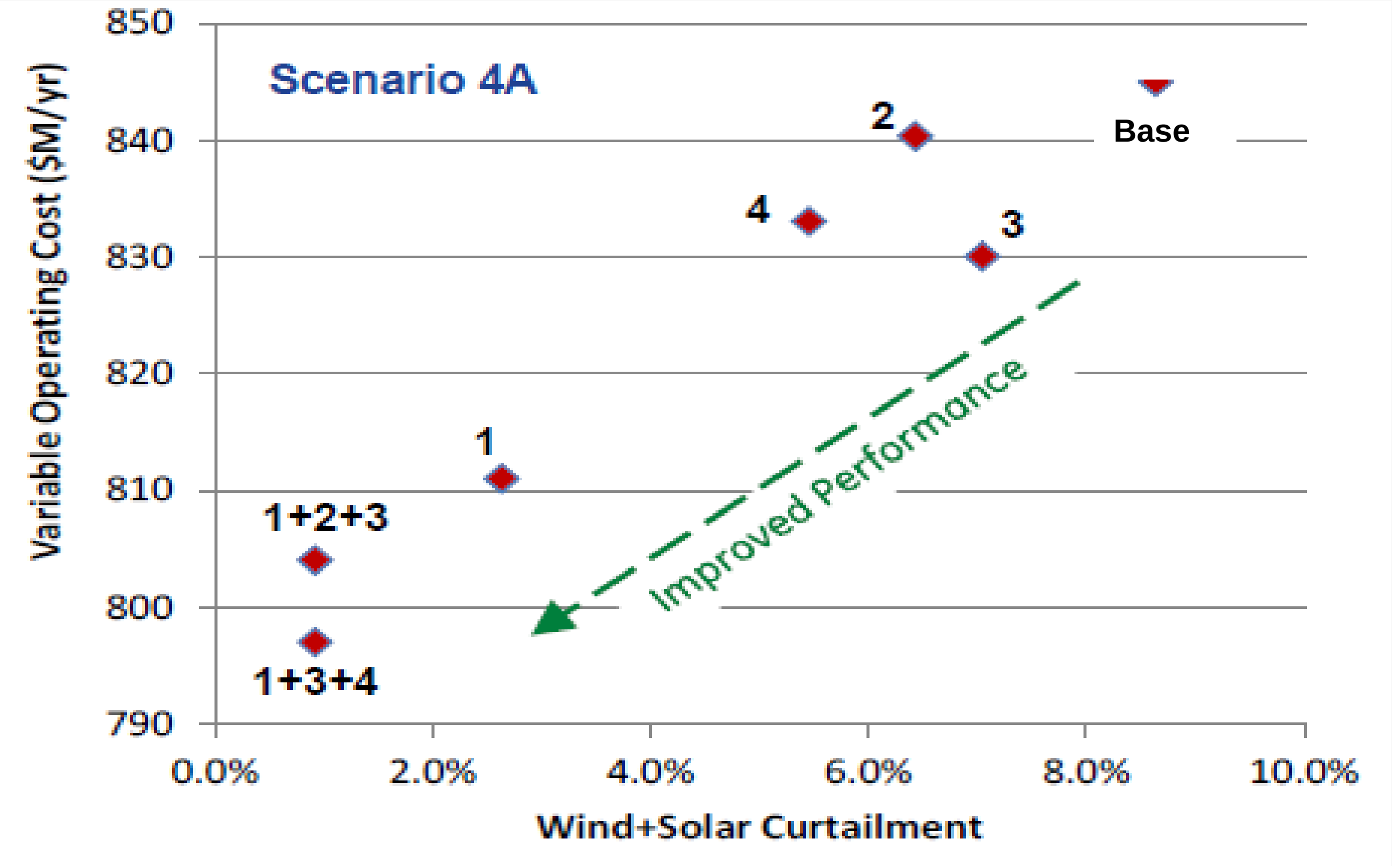
- A comparison between the two systems illustrates the system-specific differences in quantifying integration costs.
- While in the best case, solar PV reduces the amount of thermal power plants needed, in the worst case the same amount of power plants is needed as before. This leads to a different effect on the average cost per unit of electricity produced by thermal power plants.
- The key driver of these differences in cost is the higher capacity of thermal power plants needed in the worst-case situation and the cost for having these available despite their lower utilization.

System Operations

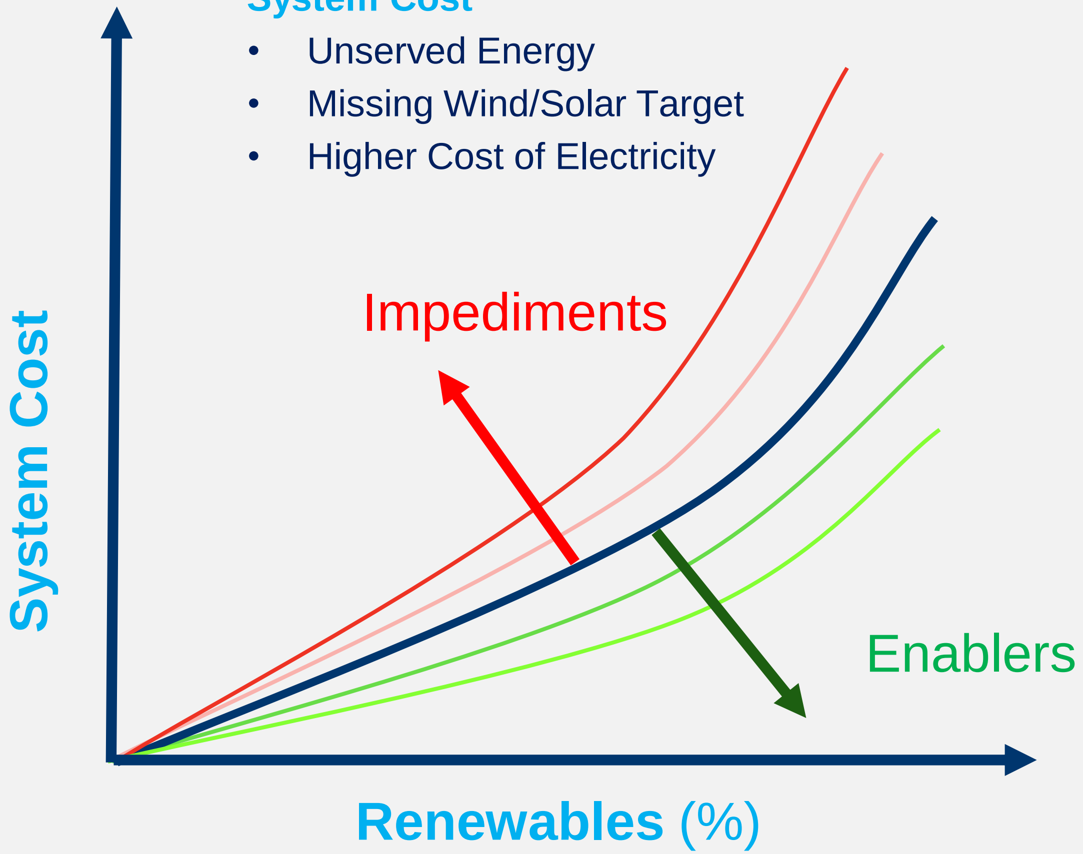
Containing curtailment

Operation Scenarios

1. Reduced thermal minimums
1. Removal of “must-run” practices
1. Changes to operating reserves
1. Down reserves from renewables



Renewable experience



System Cost

- Unserved Energy
- Missing Wind/Solar Target
- Higher Cost of Electricity

Enablers

- Wind forecasting
- Flexible thermal fleet
  - Faster quick starts
  - Deeper turn-down
  - Faster ramps
- More spatial diversity of wind/solar
- Grid-friendly wind and solar
- Demand response ancillary services
- Energy storage and electric vehicles
- Markets & Grid Codes

Impediments

- Lack of transmission
- Lack of control area cooperation
- Unobservable & uncontrollable DG – “behind the fence”
- Inflexible operation strategies
- Markets & Grid Codes

Summary of potential integration solutions

Integration Solution	Scope
More spatial diversity of wind/solar	Spreading renewable generation over a wider area
State-of-the-Art renewable forecasting	Using State-of-the-Art tools to forecast RE generation in operations
Larger balancing areas	Regional coordination to more efficiently dispatch renewable generation
Ancillary service mechanisms	Mechanisms to procure balancing services such as regulation and replacement reserves
Shorter scheduling and dispatch intervals	Shorter scheduling and dispatch intervals incorporating renewable generation forecasts
Grid-friendly wind and solar generation	Equipping and allowing renewable generation to provide ancillary services
Flexible thermal fleet (faster starts, deeper turn-downs, faster ramps)	Requiring flexibility attributes in new and existing thermal generators
Energy storage	Using energy storage to provide balancing services
Advanced demand response	Using demand response to provide balancing services

Summary

The question is not “How much RE can you install?”

The question is “What do you need to do to integrate it?”

- High renewable penetrations may require:
  - Flexibility from thermal fleet
  - Grid-friendly renewable power plants and controls
  - RE forecasting
  - Cooperation between balancing areas
  - New operation strategy (Higher reserve margin, energy storage, etc.)
- Overall operational cost depends on generation mix, emissions targets, REC certificates, etc.
- SV is a better indicator as compared to COE.

Shared Prosperity Dignified Life

Questions?

Economic and Social Commission for Western Asia

Integration Costs of Wind and Solar Power

July 30-31, Amman, Jordan

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