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ESMAP-SAR-EAP Renewable Energy Training Program 2014

Renewable Integration – The Impact to the Grid

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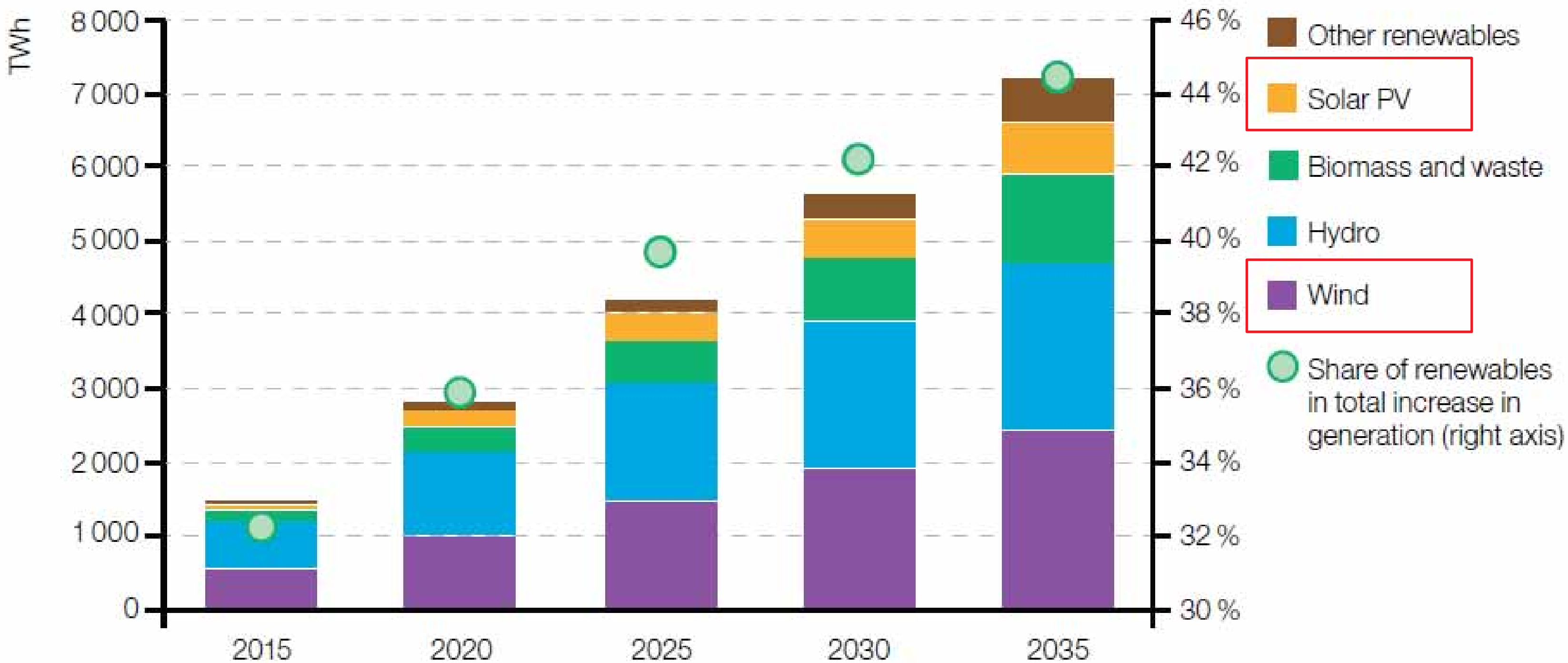
Layout

- **Basics of renewable integration**
  - Wind energy
  - Solar energy
  - Transmission
- **Challenges of integrating and scaling up renewable energy**
  - Challenges & barriers of increasing the penetration of renewable energy
  - Overview of solutions
- **Importance of renewable energy forecasting in grid operation**
- **Q&A**

Renewable energy capacity

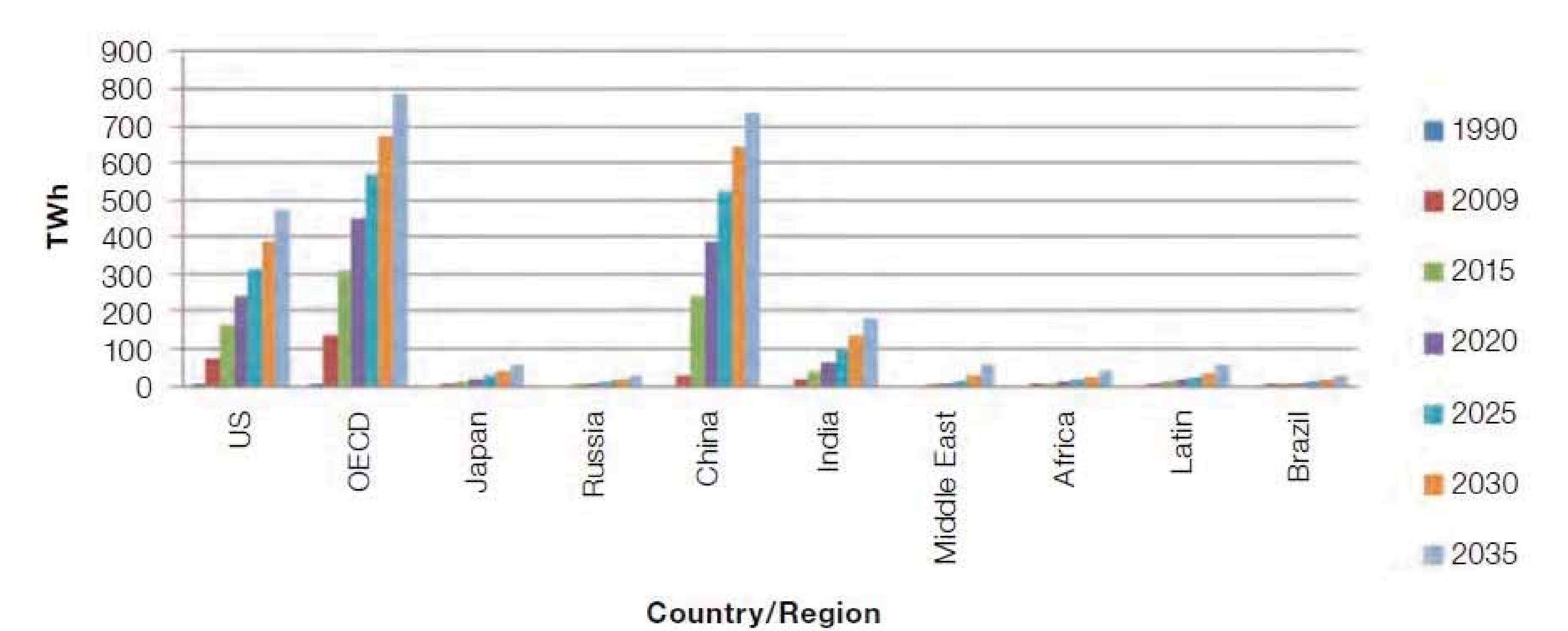
- Growth in renewables accounts for nearly half of the total increase in generation by 2035;
- A full third of global electricity generation will be supplied by RE (including hydroelectricity) by 2035.



Incremental global renewables-based electricity generation relative to 2009

IEC white paper *Grid integration of large capacity renewable energy sources and use of large capacity electrical energy storage*

Global wind energy projection to 2035



Wind energy generation by 2035 by region/countries

IEC white paper *Grid integration of large capacity renewable energy sources and use of large capacity electrical energy storage*

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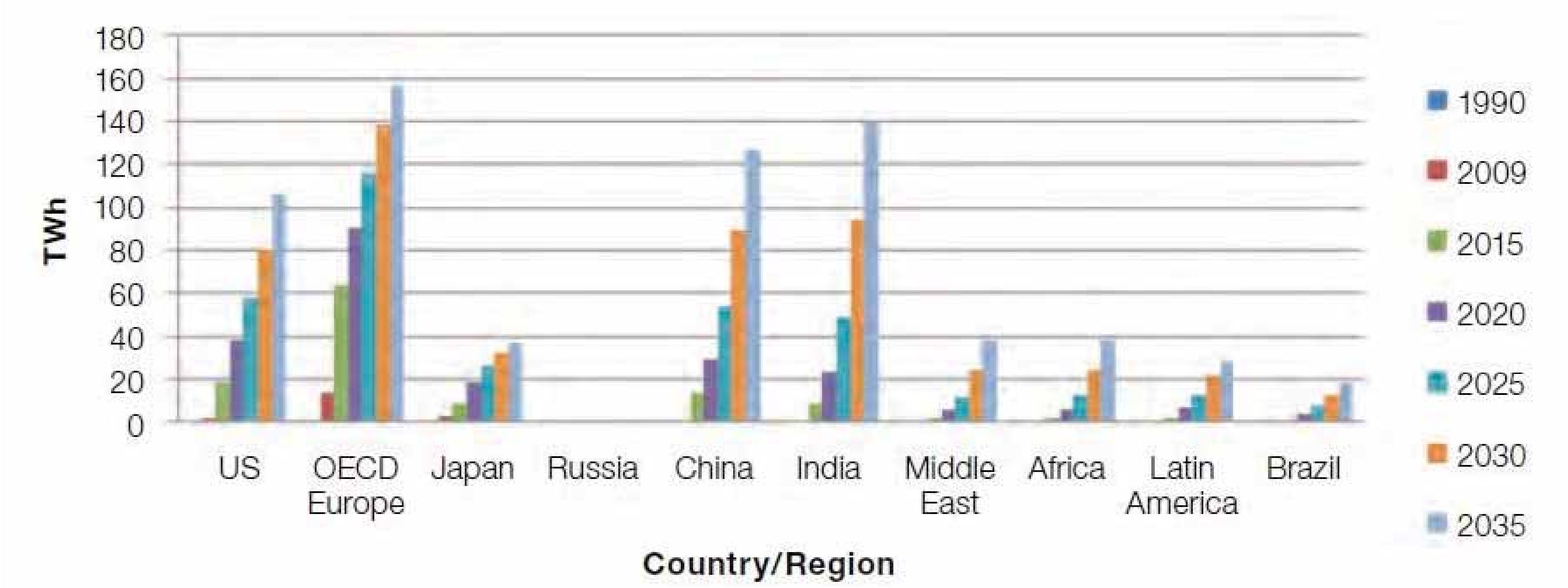
Global solar PV energy projection to 2035



Solar PV energy generation by 2035 by region/countries

IEC white paper *Grid integration of large capacity renewable energy sources and use of large capacity electrical energy storage*

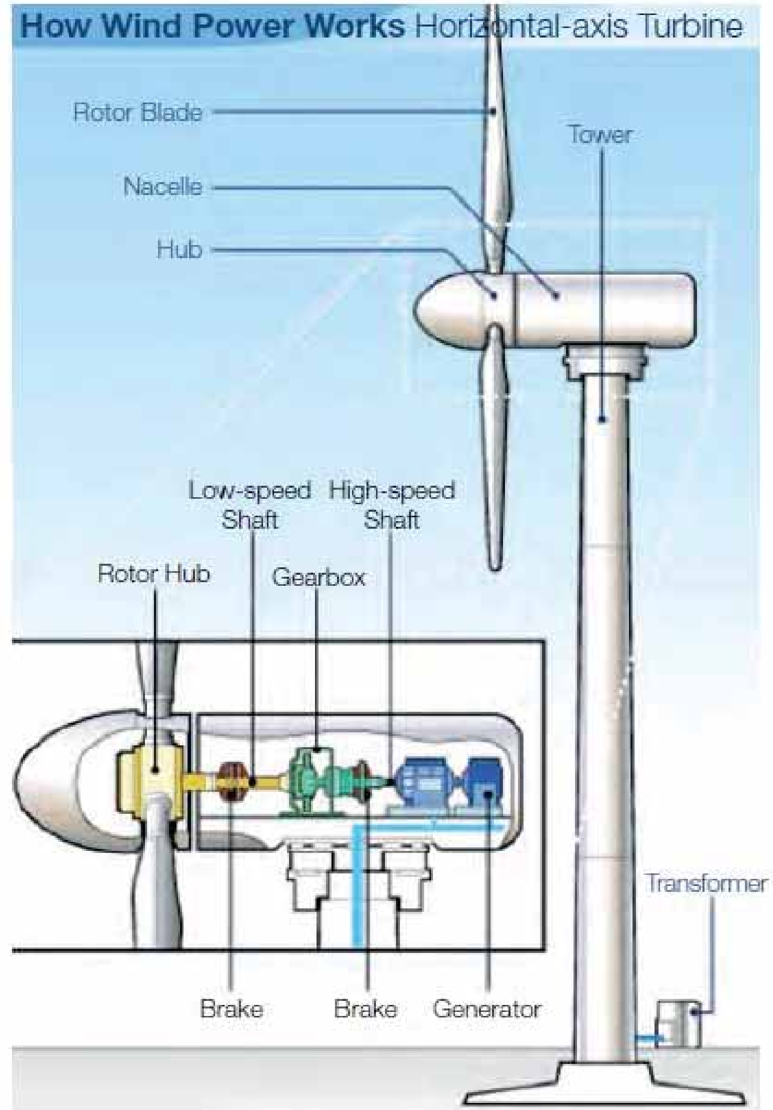
RE generation basics – wind power generation

- Wind turbine generators (WTGs) extract energy from wind and convert it into electricity via an aerodynamic rotor, which is connected by a transmission system to an electric generator.
- In general, a WTG can begin to produce power in winds of about 3 m/s and reach its maximum output around 10 m/s to 13 m/s.
- Power output

$$P_{wind} \propto [\text{blade swept area}]$$

$$P_{wind} \propto [\text{blade length}]^2$$

$$P_{wind} \propto [\text{wind speed}]^3$$



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RE generation basics – wind power generation

$P_{wind} \propto [\text{blade length}]^2$

- Generally, the longer the blade, the higher power it could generate.

model	capacity	blade length*
GE 1.5s	1.5 MW	35.25 m (116 ft)
Mitsubishi MWT95	2.4 MW	47.5 m (156 ft)
Vestas V100	2.75 MW	50 m (164 ft)
Vestas V112	3.0 MW	56 m (184 ft)

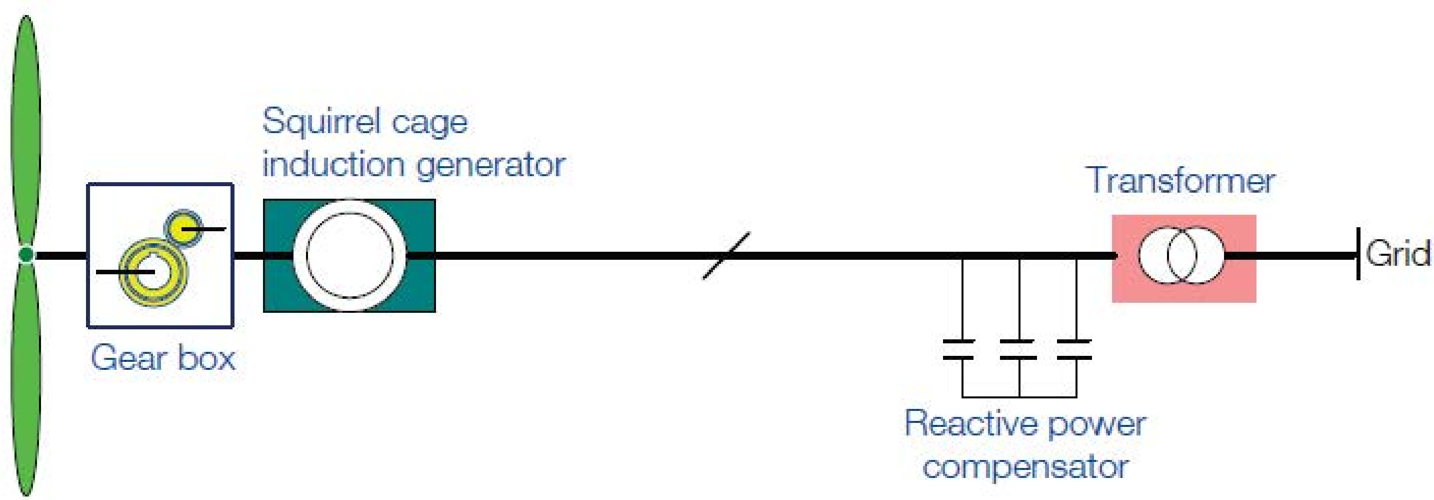
- In Feb 2014, Vestas claimed the crown of the world's largest wind turbine.
- Capacity: 8 MW
- Blade length: 80 meters
- Tower height: 140 meters
- Swept area: 20,100 m^2

The 83.5 meter long blades blades from Danish SSP Technology have been transported to Scotland last month and will be installed on a 7 MW test offshore turbine for Samsung Heavy Industries' first offshore wind energy project, targeted to start in 2015.

RE generation basics – wind power generation

Type #1: fixed speed induction generation (1980s)

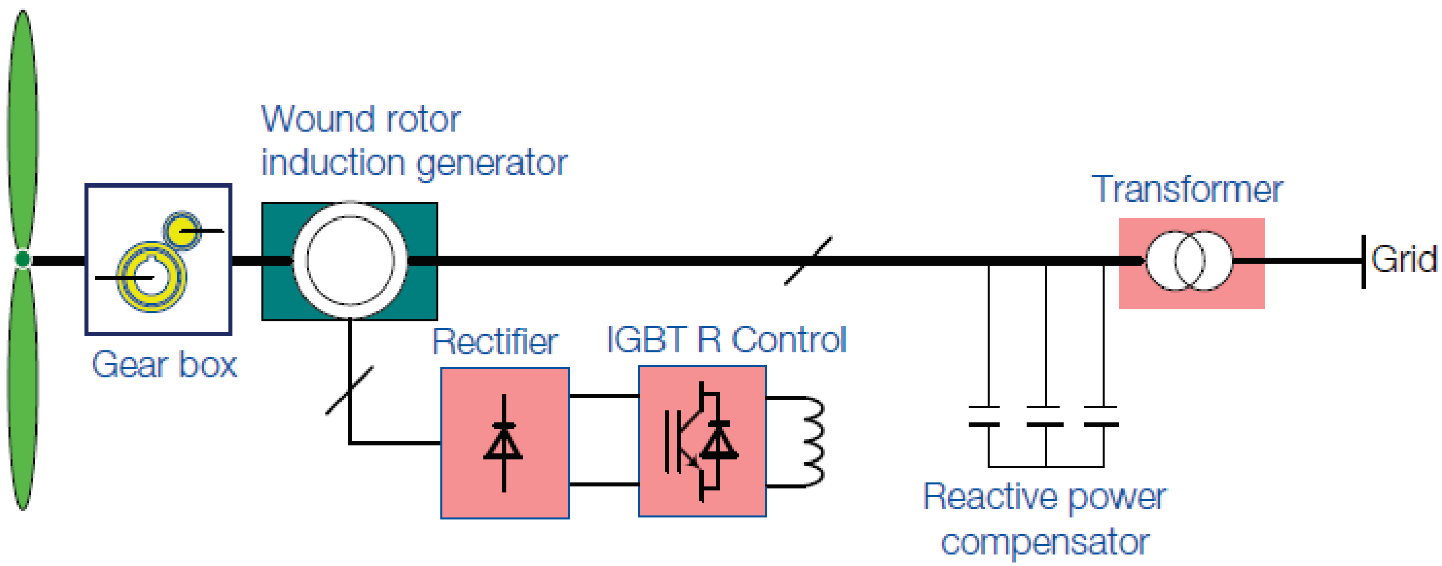
- Speed varies only 1-2%, almost fixed → can't rotate in low wind → low efficiency of using wind energy
- Induction generator absorbs reactive power → requires compensating reactive power



RE generation basics – wind power generation

Type #2: variable-slip induction generator (1980s – 1990s)

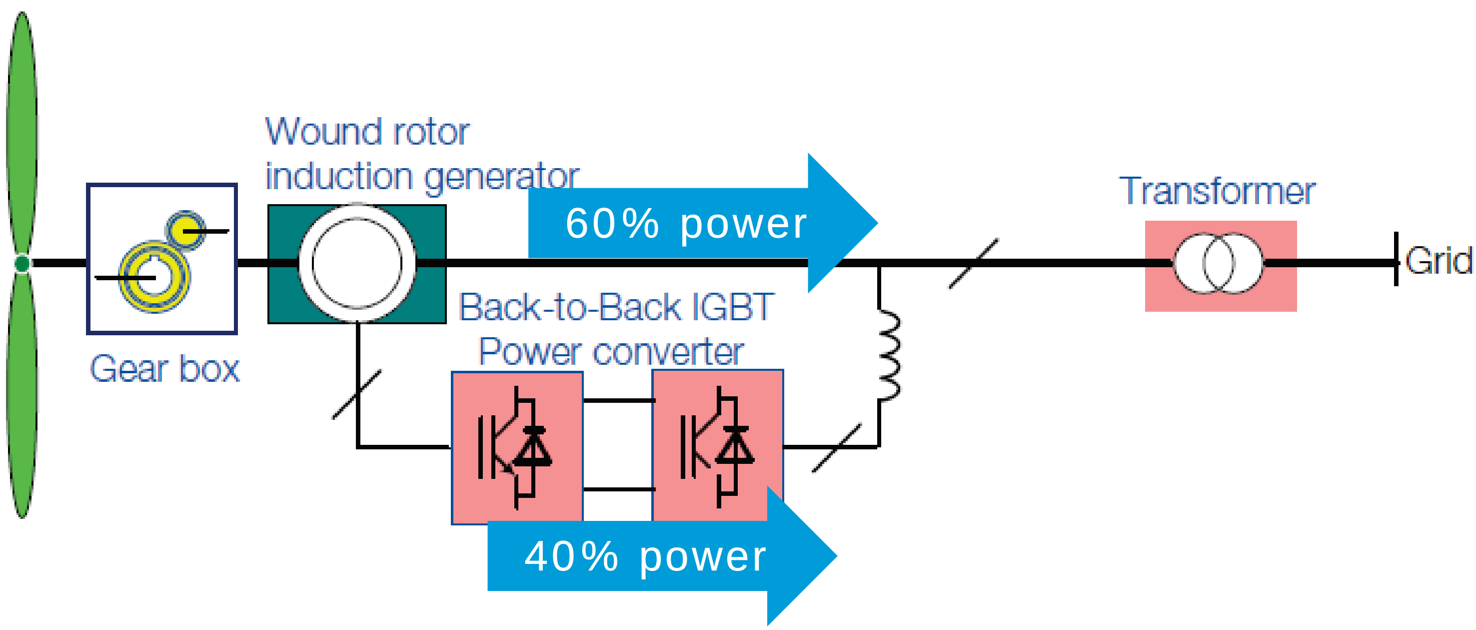
- Power electronics components to control magnitude of rotor current → allows rotor speed varies ±10% → enhanced efficiency
- From mechanical perspective, if rotor speed varies when torque varies, it will reduce wear and tear of gear box.



RE generation basics – wind power generation

Type #3: Double-fed induction generator (DFIG) – most popular at present

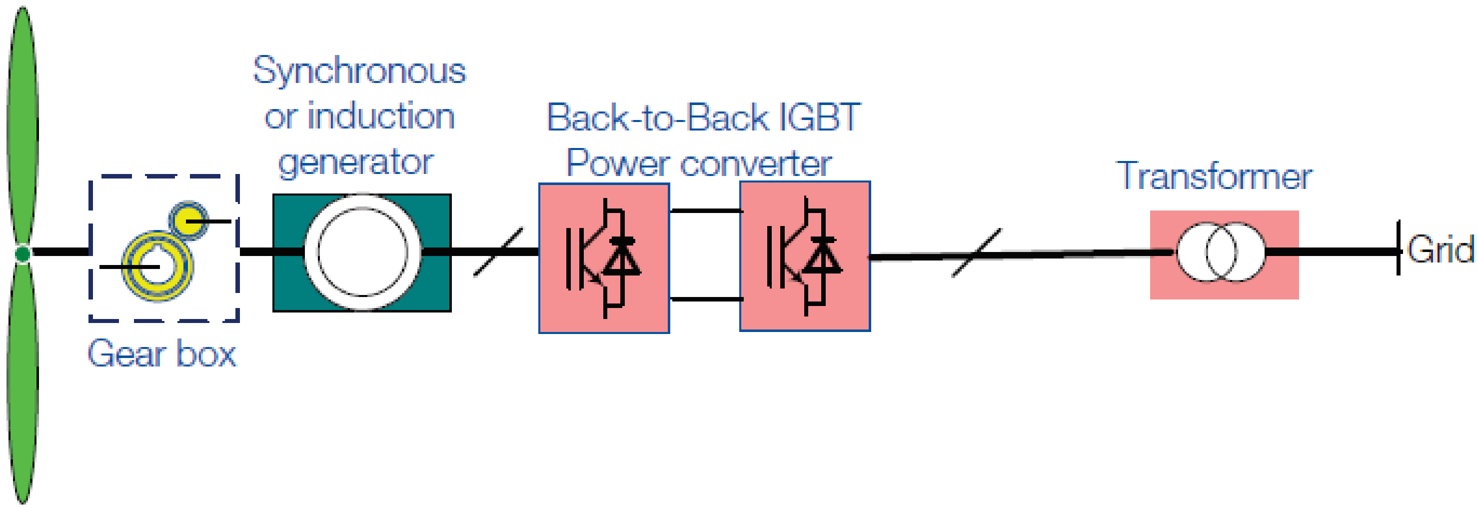
- IGBT converters to control both magnitude and frequency of rotor current;
- Up to 40% of generator power goes thru converter to the grid; the rest goes directly to the grid;
- This enables ±40% speed variation; remove the need of reactive power compensation.



RE generation basics – wind power generation

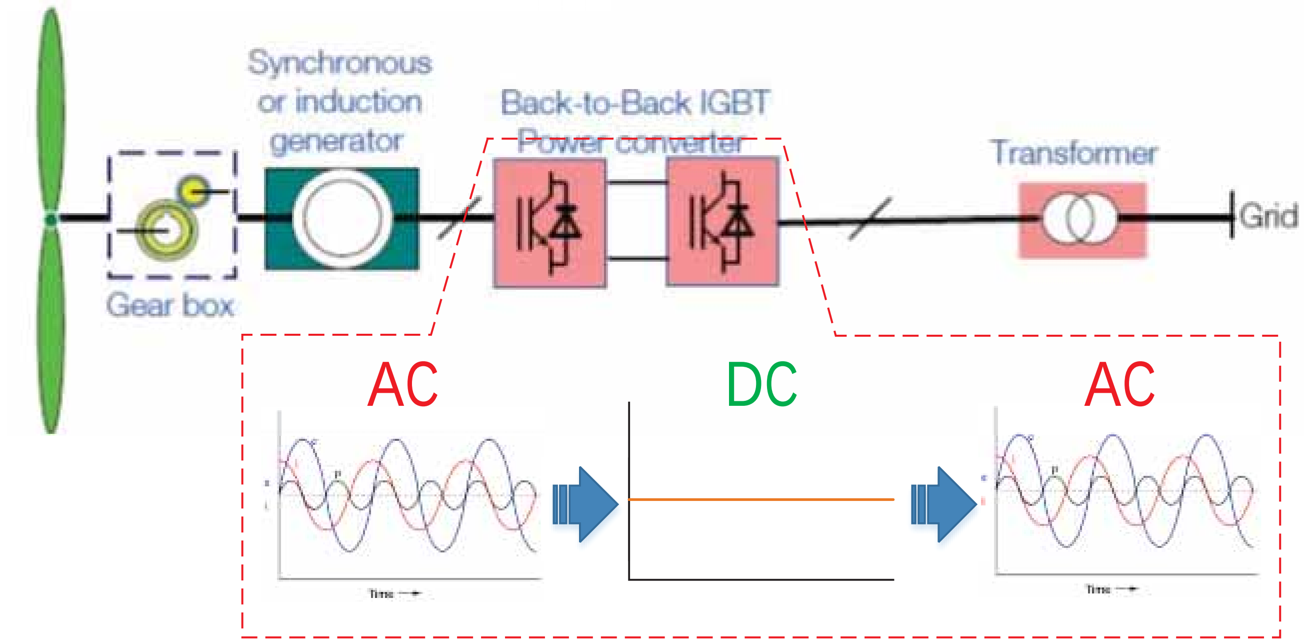
Type #4: Full-power conversion generation

- Completely decoupled → all the power goes thru converter to the grid;
- Wider range of speed variation; fully control of active and reactive power;
- Output current could be modulated to zero → no short-circuit current



RE generation basics – wind power generation

Full-power conversion generation

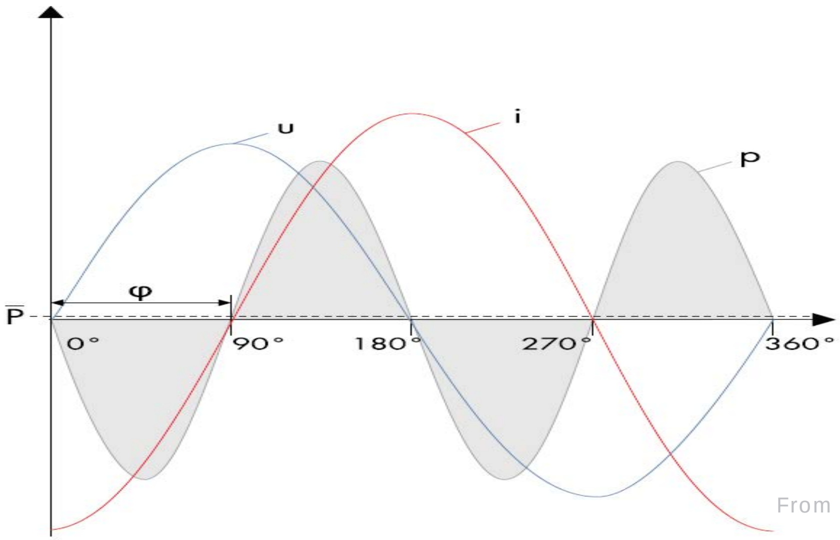


- Thanks to the power electronics' nature of AC/DC/AC conversion, it can fully manipulate the amount & magnitude of reactive power Q.

RE generation basics – wind power generation

1. What is reactive power? Side dish

   – A phase shift of voltage and current;



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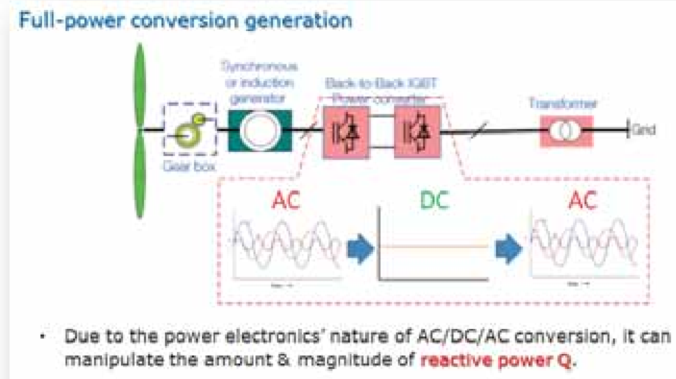
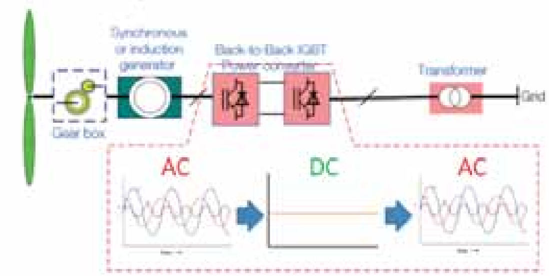


- Inductive equipment (induction motor / generator, transformer, transmission line) consumes reactive power – *I* to lag behind *V*;
- Capacitive equipment (capacitor) generates reactive power – *V* to lag behind *I*;

RE generation basics – wind power generation

2. Why is reactive power so important?
   - Reactive power (Var) is required to maintain the voltage to deliver active power (watts) through transmission lines.
   - Motor and other loads require reactive power to build up magnetic field.
   - When there is not enough reactive power, the voltage sags down and it is not possible to push the power demanded by loads through the lines.
   - It is very useful for controlling voltage.

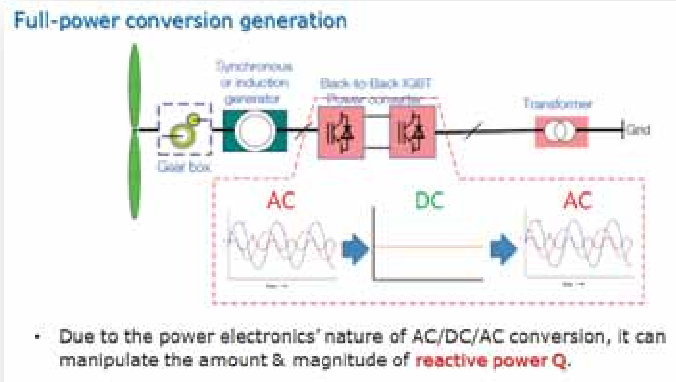
Full-power conversion generation



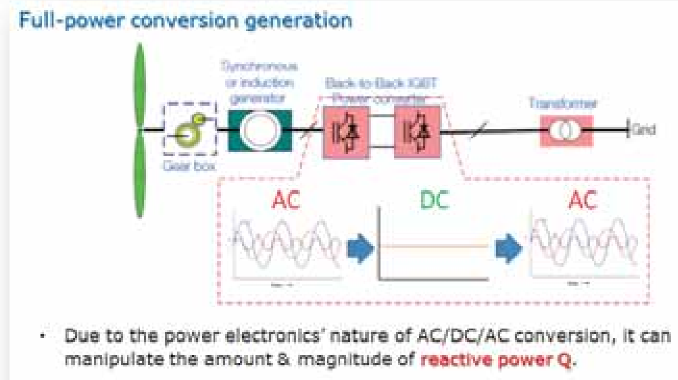
- Due to the power electronics' nature of AC/DC/AC conversion, it can manipulate the amount & magnitude of reactive power Q.

RE generation basics – wind power generation

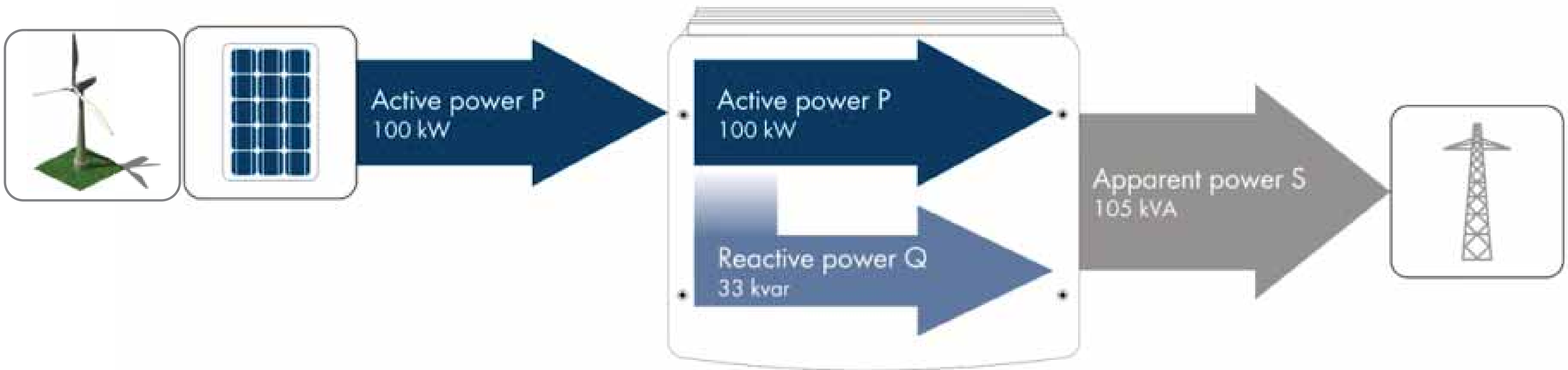
3. Beauty of reactive power
   - It can be generated / absorbed purely by power electronic converter.
   - Any wind turbine with such converter can play a role in voltage control while generating real power (kW).
   - An electrical energy storage (EES) can generate / absorb reactive power WITHOUT using its real energy (kWh), i.e. without changing its State Of Charge (SOC). → using reactive power has NO time limit.

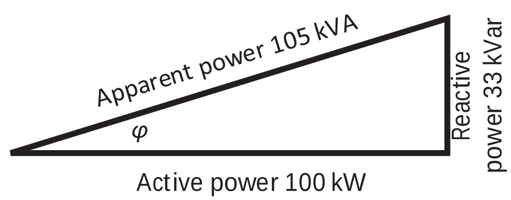


RE generation basics – wind power generation



Independence with active power





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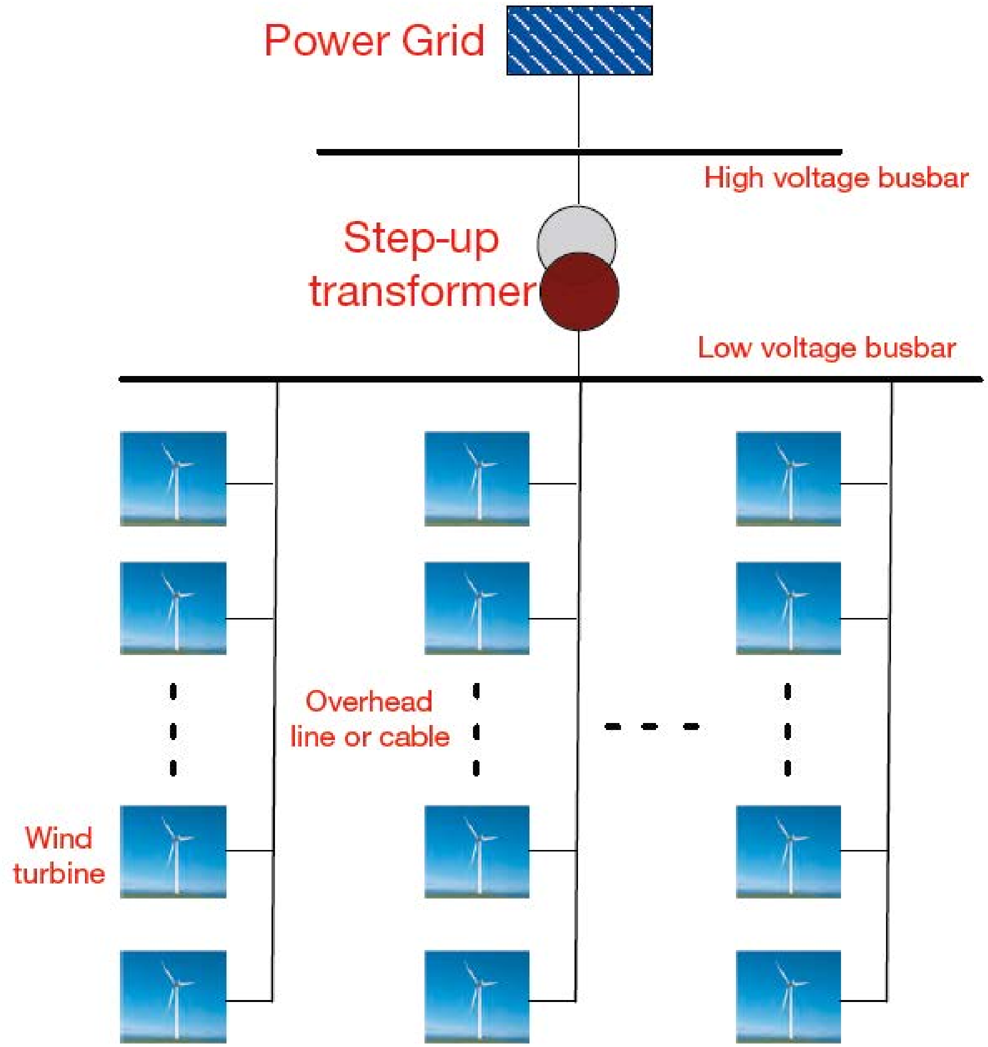
RE generation basics – wind power generation

- Capacity of a single wind turbine is very limited, non-comparable to traditional power plant.

- To make the capacity comparable, a wind farm consists of many wind turbines.



RE generation basics – wind power generation

Wind farm

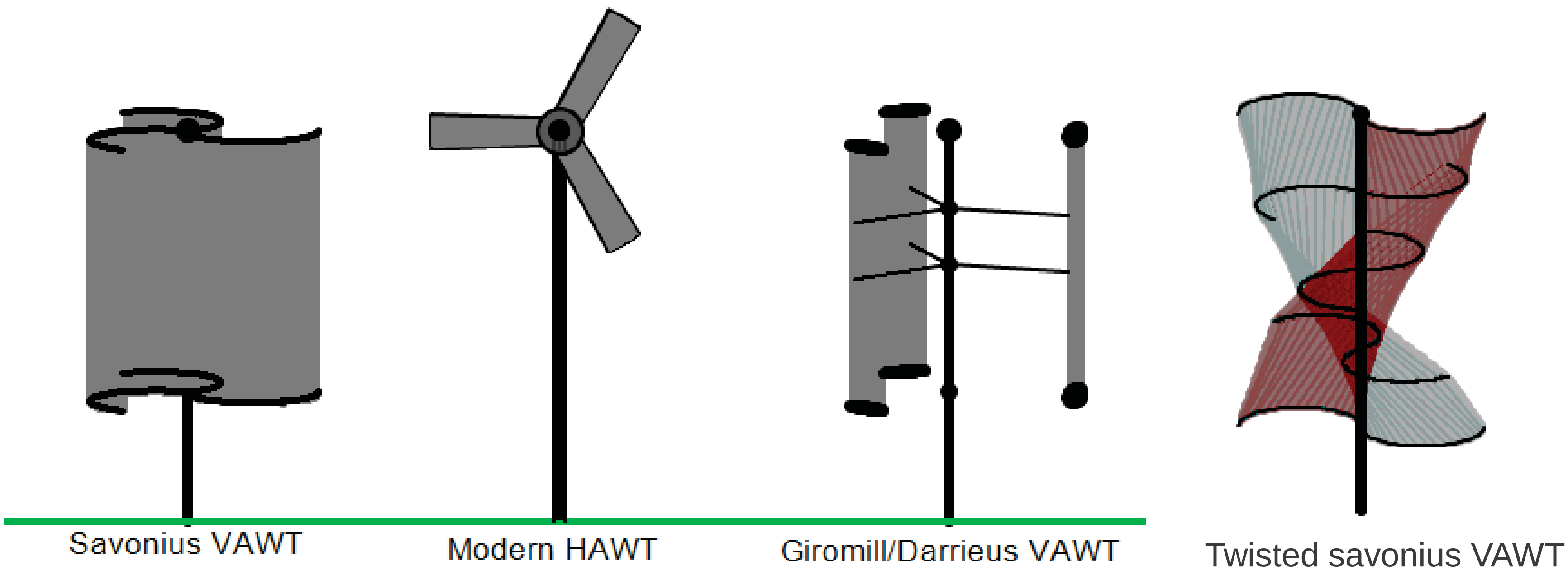
- Current largest onshore wind farm – China Gansu wind farm has capacity 5GW (*almost enough to cover entire Singapore*), which is to be expanded to 20GW by 2020!

- Current largest offshore wind farm – UK's *London Array* with capacity 650MW

RE generation basics – wind power generation

VAWT: vertical axis wind turbine;

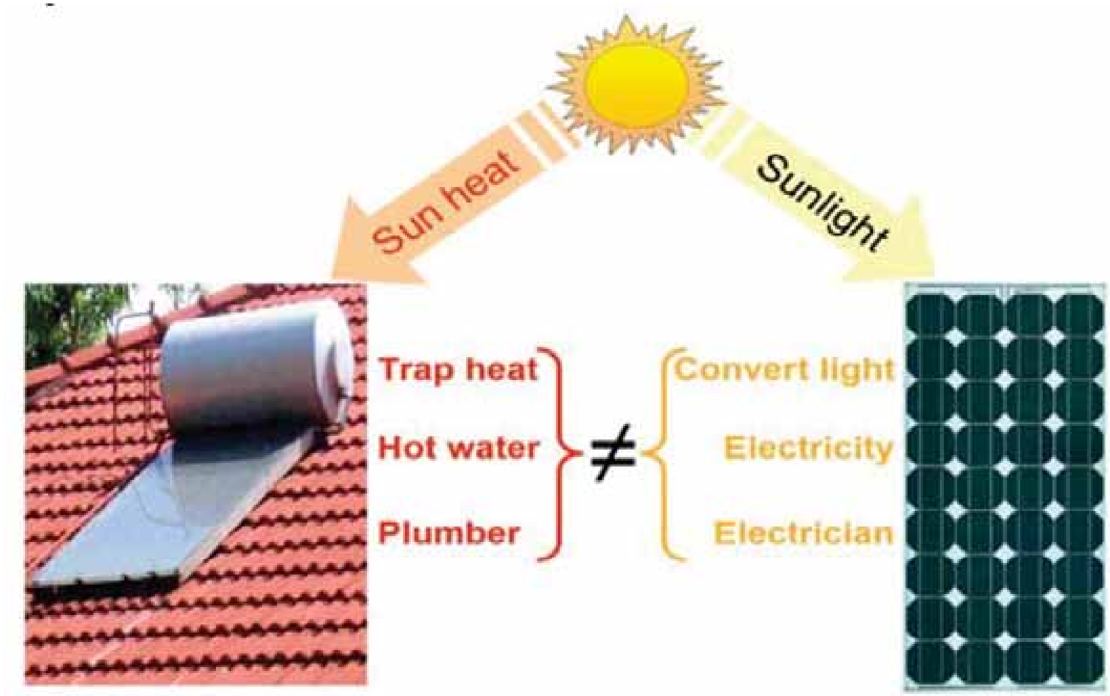
HAWT: horizontal axis wind turbine;



More information can be found in wikipedia

RE generation basics – solar PV power

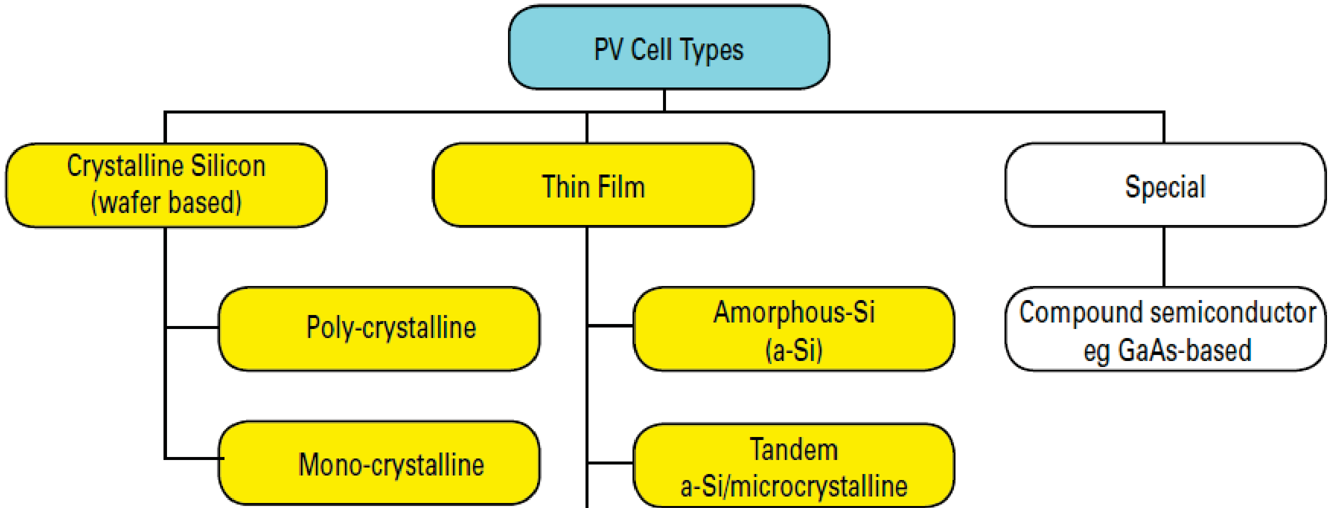
- The sun delivers its energy to us in two main forms: heat and light.
- Two main types of solar power systems, namely, solar thermal systems that trap heat to warm up water, and solar PV systems that convert sunlight directly into electricity

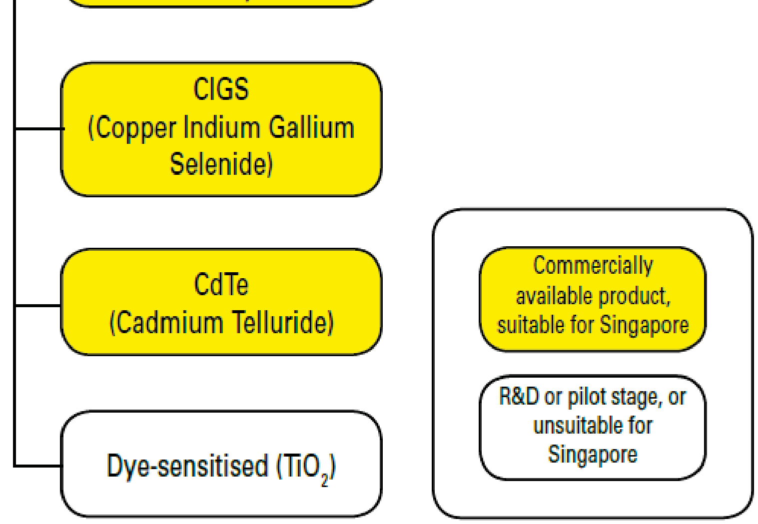


Singapore EMA *Handbook for solar PV system*

RE generation basics – solar PV power

Types of solar PV penal





Mono-crystalline silicon | **Poly-crystalline silicon** | **CIGS thin film**

Singapore EMA *Handbook for solar PV system*

RE generation basics – solar PV power

- Different types of solar PV has different conversion efficiency, as illustrated

$$\eta = \frac{P_m}{E \times A_c}$$

- where: *Pm* is electrical power at maximum power point (watt), *E* is sunlight irradiance (watt/m2), and Ac is surface area (m2).
- Solar cell efficiencies are measured under standard test conditions (STC): temperature of 25 °C, and sunlight irradiance of 1000 W/m^2 .

Efficiency at rated temperature (25°C)

Technology	Module Efficiency
Mono-crystalline Silicon	12.5-15%
Poly-crystalline Silicon	11-14%
Copper Indium Gallium Selenide (CIGS)	10-13%
Cadmium Telluride (CdTe)	9-12%
Amorphous Silicon (a-Si)	5-7%

Singapore EMA *Handbook for solar PV system*

RE generation basics – solar PV power

In South East Asia, PV performance drops

- Performance declines while cell temperature rises

Technology	Temperature Coefficient [%/°C]
Crystalline silicon	-0.4 to -0.5
CIGS	-0.32 to -0.36
CdTe	-0.25
a-Si	-0.21

- For example, in bright sunlight, cell temperatures in Singapore can reach over 70ºC, whereas rated cell temperature is 25ºC. Therefore the actual module efficiency loss at 70ºC is measured as (use mono as example)

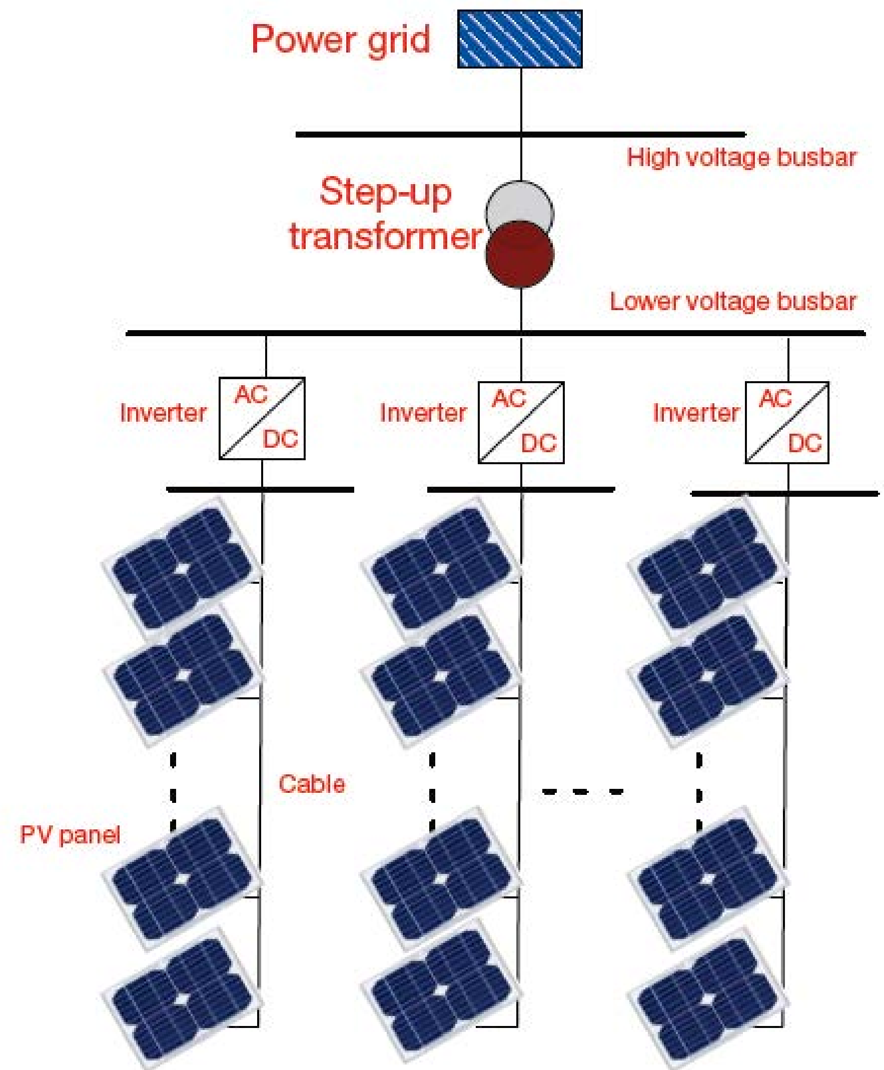
$$(70 - 25) * 0.5\% = 22.5\%$$

Singapore EMA *Handbook for solar PV system*

RE generation basics – solar PV power

- PV cells are connected in series and in parallel to one another to form PV modules with capacities of typically 50 W-200 W.

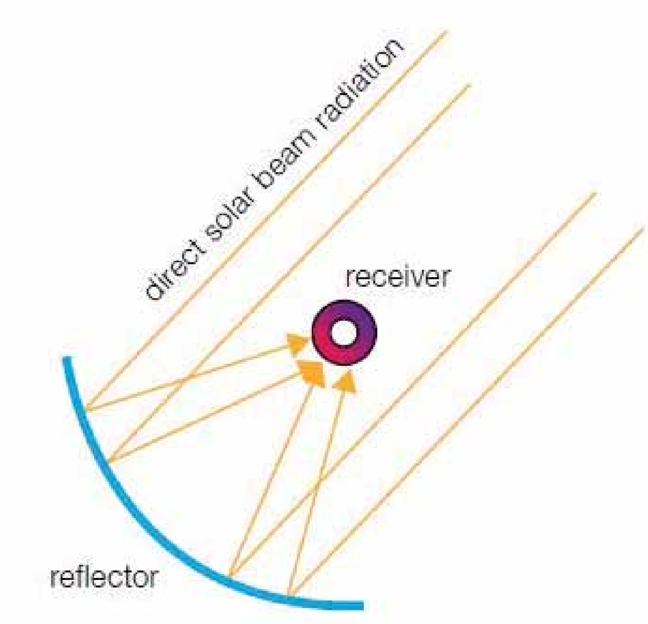
- Large utility-scale PV systems are usually called PV power station, or PV farm.

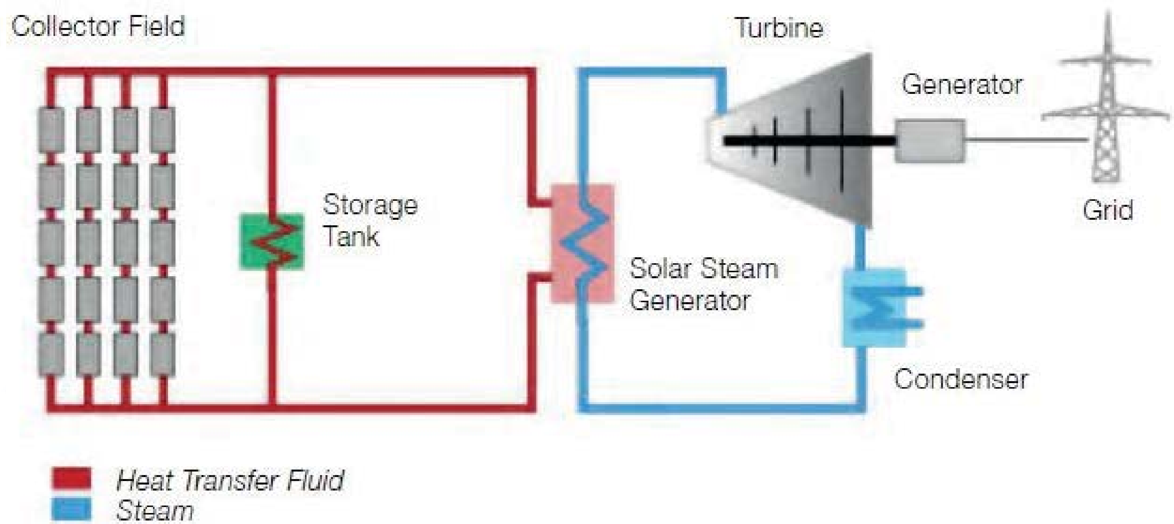


IEC white paper *Grid integration of large capacity renewable energy sources and use of large capacity electrical energy storage*

RE generation basics – concentrated solar power (CSP)

- Concentrated solar thermal power to heat up fluid





IEC white paper *Grid integration of large capacity renewable energy sources and use of large capacity electrical energy storage*

RE generation basics – concentrated solar power (CSP)

(a) Parabolic trough system
(b) Linear Fresnel reflector (LFR)
(c) Solar tower
(d) Parabolic dish

RE generation basics – Transmission

Large-capacity RE generation plants are usually far from load centres, and they therefore need long-distance power transmission.

1. AC transmission: most popular and mature. Used for large capacity RE power transmission (China and USA);

2. Voltage source converter high voltage DC (VSC-HVDC) transmission: popularly used for offshore wind power integration (Europe).

3. Ultra-high voltage AC (UHVAC) and current source converter HV/UHVDC (CSC-UHVDC)

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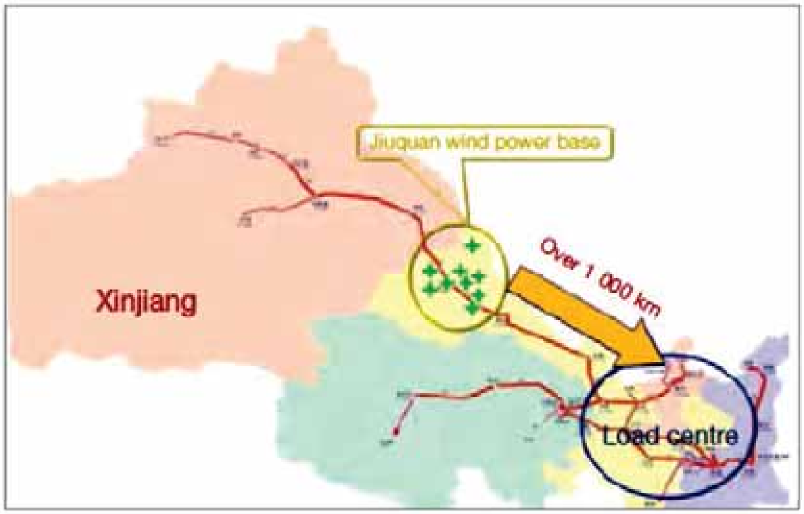
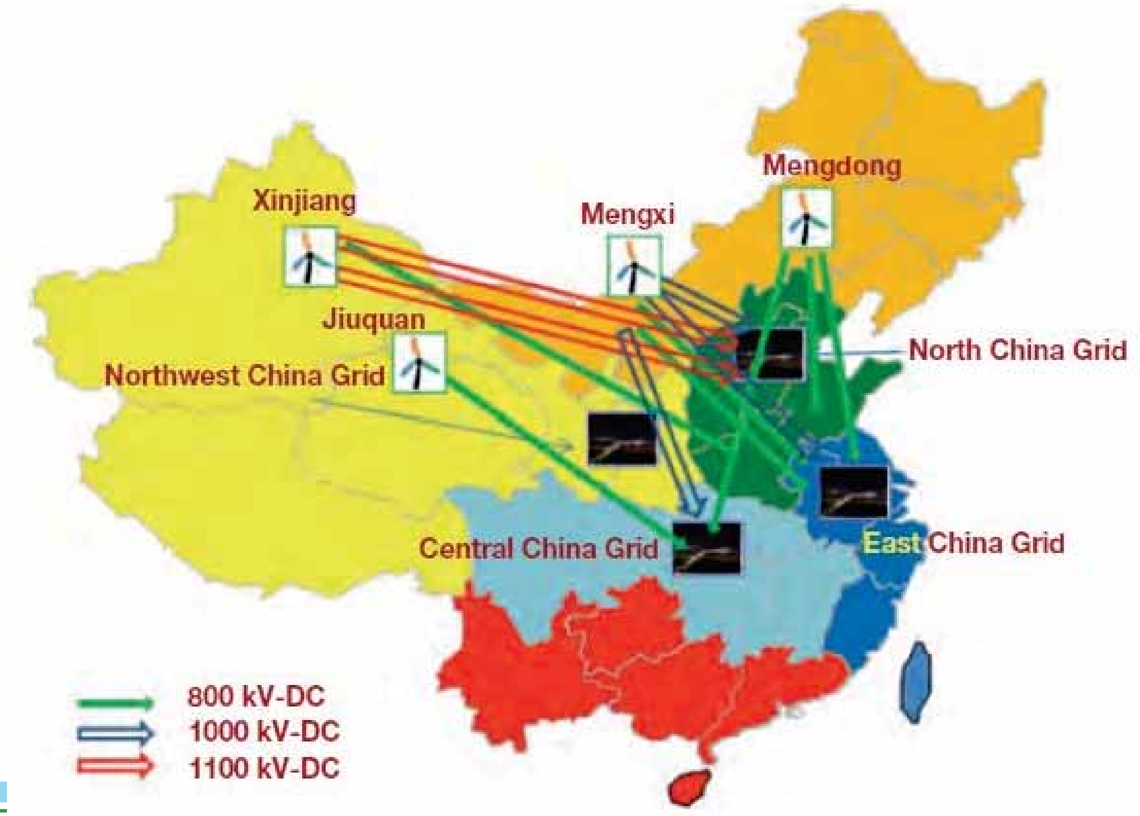
RE generation basics – Transmission

- UHVAC transmission lines with rated voltage levels of 1,150 kV or 1,000 kV were built and commissioned by the former Soviet Union and Japan in the 1980s and 1990s, but then operated at a 500 kV voltage level for practical reasons.
- China is now leading the research and application of 1,000 kV UHVAC transmission.
- Compared to 500 kV AC transmission, 1,000 kV AC transmission has many advantages in
  1. improving transmission capacity and distance,
  2. reducing power loss,
  3. reducing land use and saving cost.



RE generation basics – Transmission

- CSC-UHVDC is a relatively mature technology used for long-distance, large-capacity power transmission without midway drop points, as well as for the interconnection of asynchronous power networks.
- Again, China is leading the research and application UHVDC transmission.



Layout

- Basics of renewable integration
  - Wind energy
  - Solar energy
  - Transmission
- **Challenges of integrating and scaling up renewable energy**
  - Challenges & barriers of increasing the penetration of renewable energy
  - Overview of solutions
- **Importance of renewable energy forecasting in grid operation**
- **Q&A**

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Challenges of RE generation to the grid

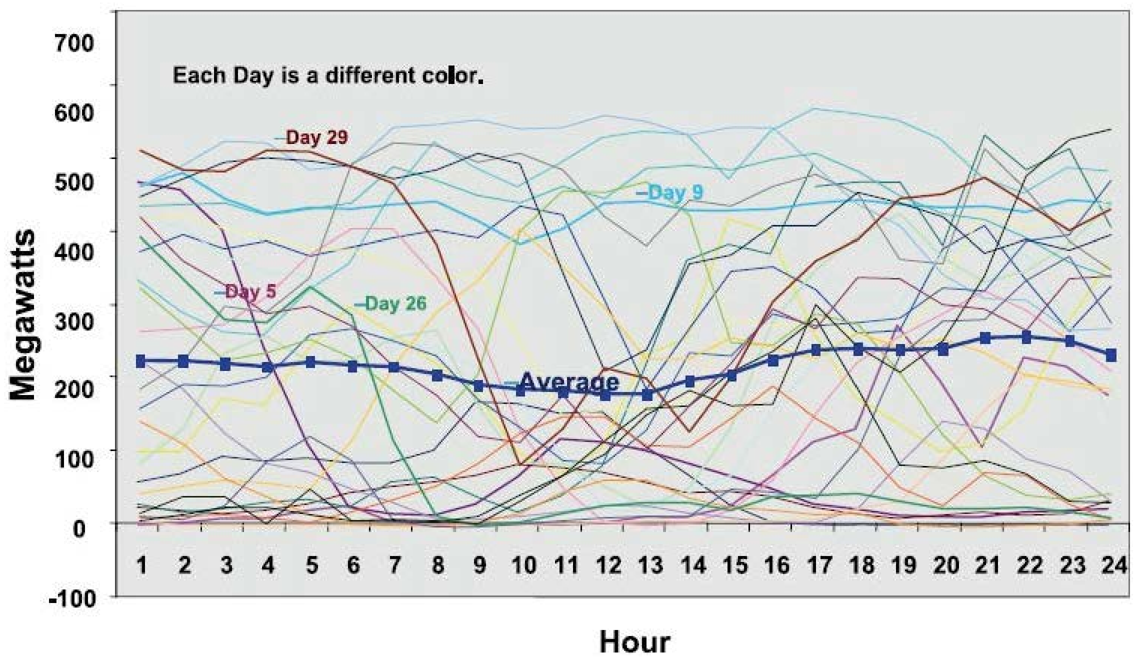
- Non-controllable variability
  – Wind and solar output varies in a way that generation operators cannot control
- Partial unpredictability
  – The availability of wind and sunlight is partially unpredictable
- Location dependence
  – The best wind and solar resources are based in specific locations

IEC white paper *Grid integration of large capacity renewable energy sources and use of large capacity electrical energy storage*

Challenges of RE generation to the grid – variability

1. Non-controllable variability

- The variability of wind and solar generation affects the system at the moment-to-moment time scale as a cloud passes over a PV plant or the wind drops.
- This variability impacts the grid since it causes fluctuation in grid voltage and frequency.

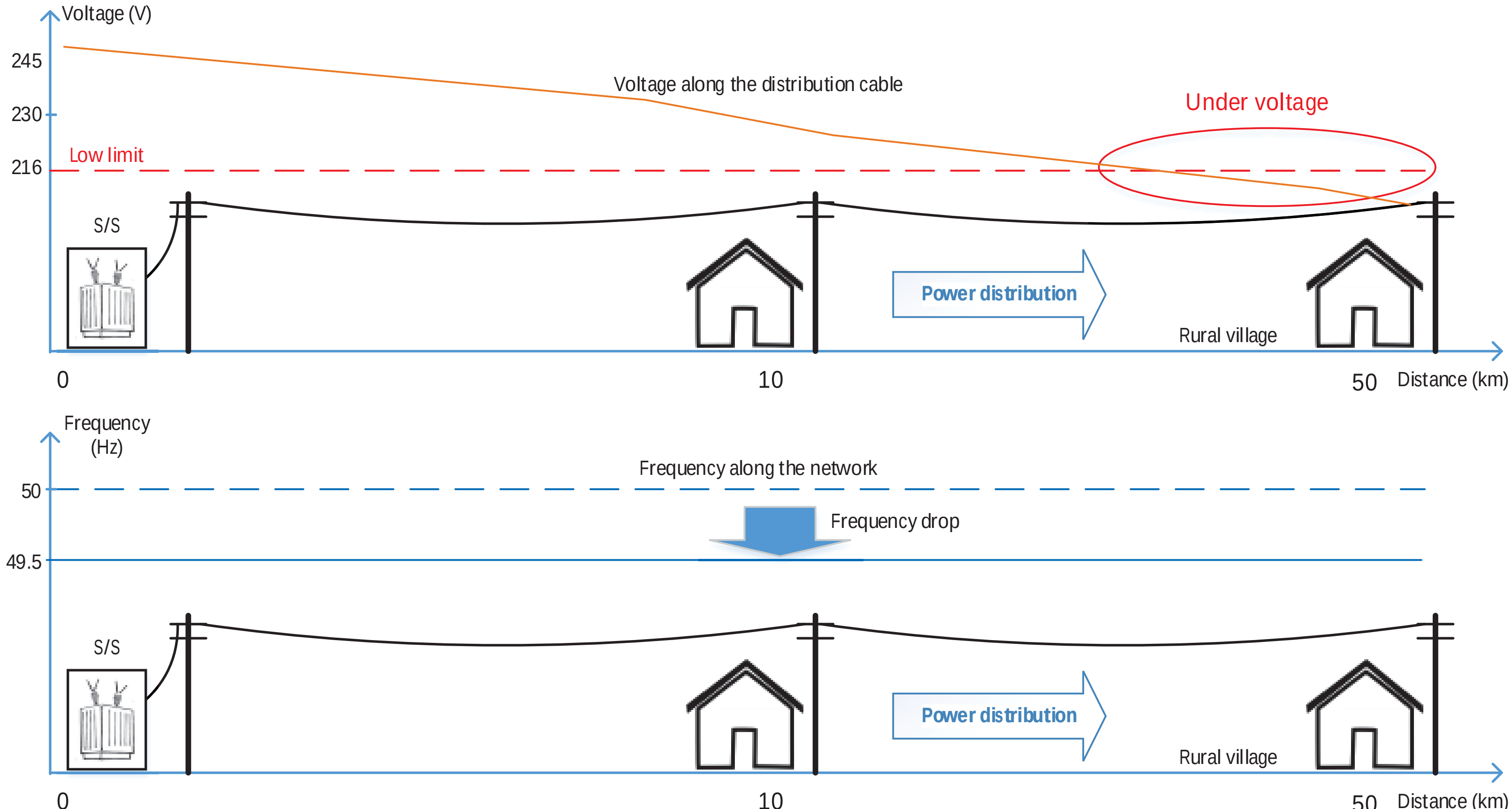


Hourly wind power output on 29 different days in April 2005 at the Tehachapi wind plant in California

- It requires grid operator to perform more complicated voltage and frequency regulation. The higher the RE penetration is, the more complicated (sometimes impossible) to manage this challenge.

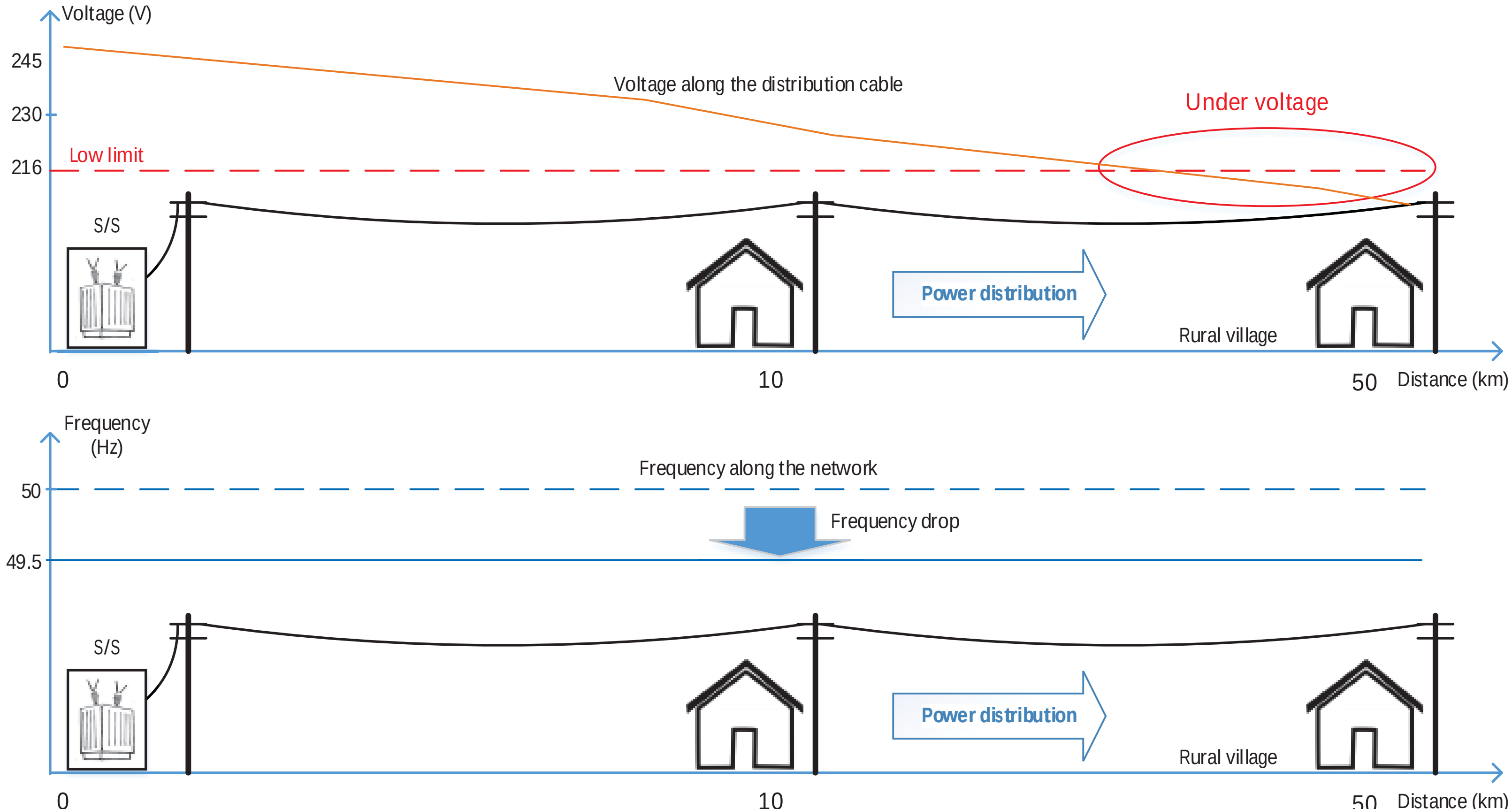
Challenges of RE generation to the grid – variability
Conventional power transmission & distribution

- Voltage drops along the cable, following $\Delta V = I * (R + jx)$
- There are several ways to solve under voltage problem, e.g. by a voltage regulator



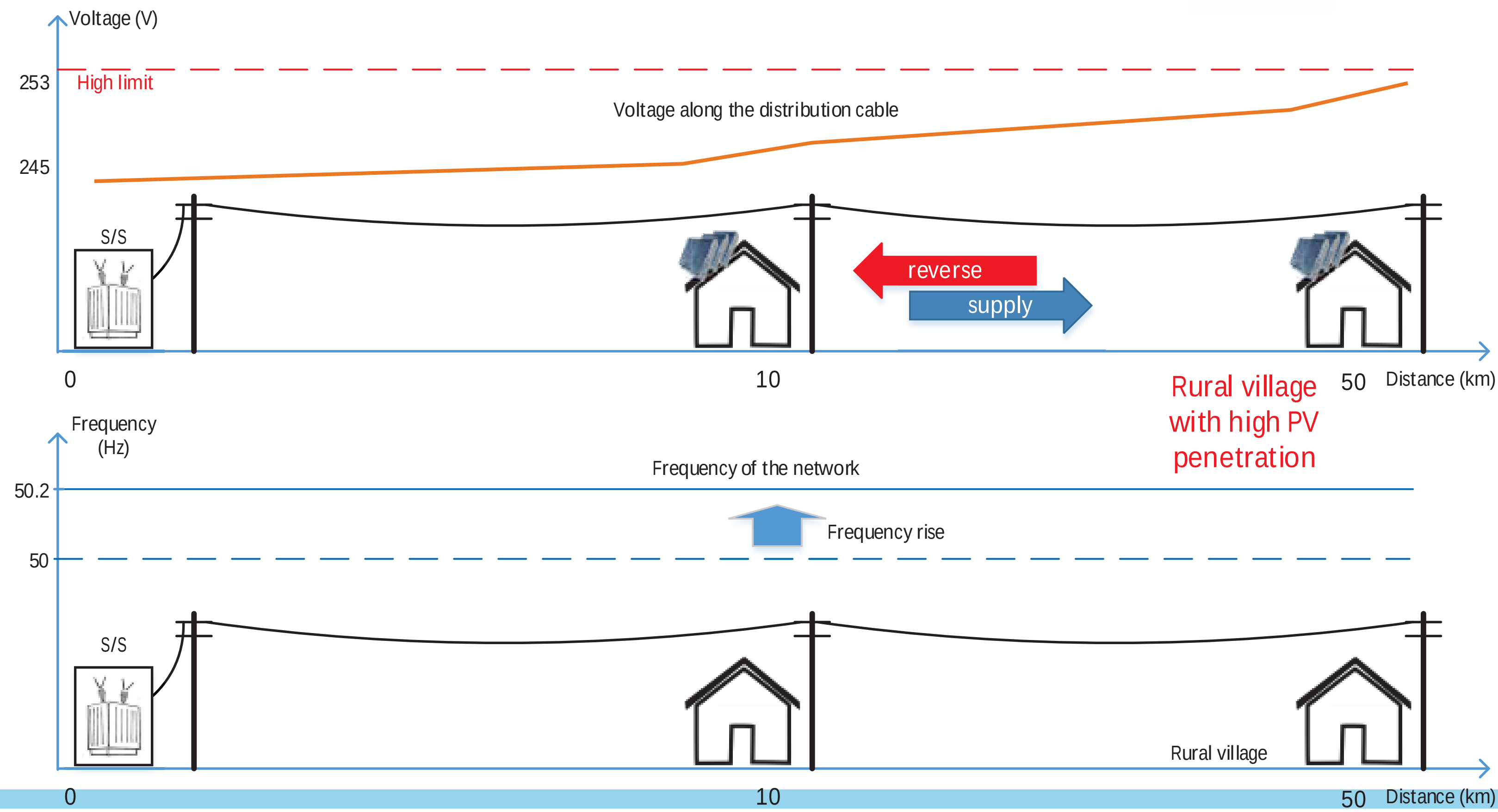
Challenges of RE generation to the grid – variability
Conventional power transmission & distribution

- In conventional power network, frequency balance between gen and load is achieved by controlling power;
- Load ↗, frequency ↘; load ↘, frequency ↗.



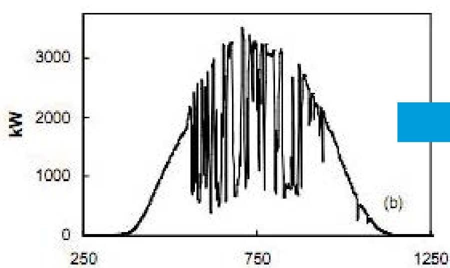
Challenges of RE generation to the grid – variability
Current power system with renewable connection - voltage

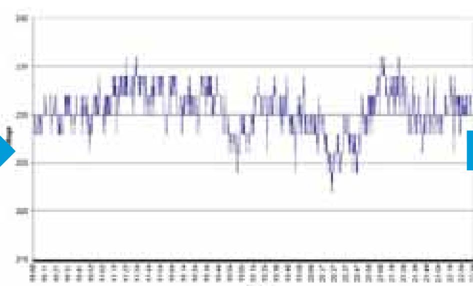
- Powerflow in the system is no longer one-direction. High penetration of renewable energy such as PV could **reverse the powerflow** of the system.
- When powerflow reversed, the voltage drop could be "**reversed**" too.
- The node with high renewable penetration could face "**over-voltage**" problem.



Current power system with renewable connection - frequency

- In conventional network the generator controls system frequency by adjusting power output;
- Since inverter-connected RE sources do not contribute to frequency control so far due to their fluctuating characteristics (e.g. wind power) or their small amount of power (e.g. solar power), renewable energy generation systems are normally operated at their maximum power output.
- Therefore, a large scale of fluctuating RE power (e.g. solar) would cause fluctuation of system frequency.
- Frequency fluctuation could cause tripping of renewable inverters → larger scale of generation loss → more instantaneous frequency drop → more renewable inverter trip → ......





Challenges of RE generation to the grid - variability

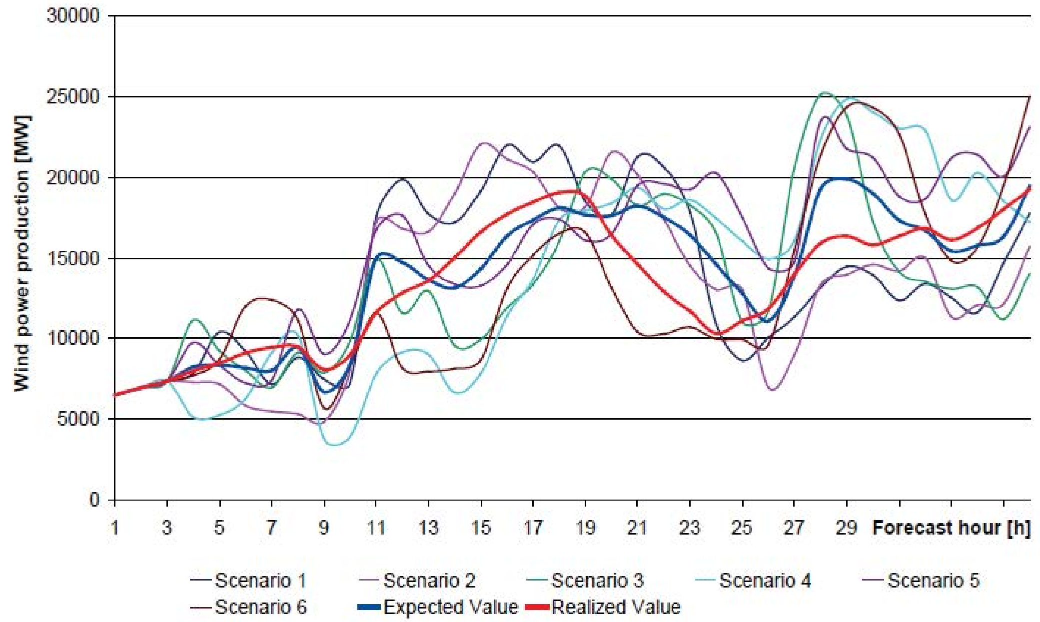
A good solution – **Electrical Energy Storage (EES)**

Role	Description	Benefits
Power quality and stability	Using active and reactive power to handle voltage spikes, sags and harmonics	Mitigates voltage instability and harmonics caused or exacerbated by uncontrollable variability of RE generation
Frequency regulation	A fast-response increase or decrease in energy output to stabilize frequency	Mitigates uncontrollable moment-to-moment variability in RE generation output
Spinning reserve	A fast-response increase or decrease in energy output to cover a contingency, e.g. generator failure	Mitigates partial unpredictability of RE generation output, providing (or removing) energy when the RE resource does not perform as expected
Load following & ramping	EES follows hourly changes in demand throughout the day	May mitigate partial unpredictability in RE output during critical load times

Challenges of RE generation to the grid - unpredictability

2. Partial unpredictability

- Partial unpredictability, also called uncertainty, refers to our inability to predict whether the wind and sun will be generally available for energy production an hour or a day from now.



Example of a day-ahead forecast scenario tree for the wind power forecast for the PJM region of the United States

- This uncertainty greatly affects Unit Commitment.
- To deal with unit commitment with such uncertainties
  - Forecasting followed by advanced unit commitment with stochastic factors.

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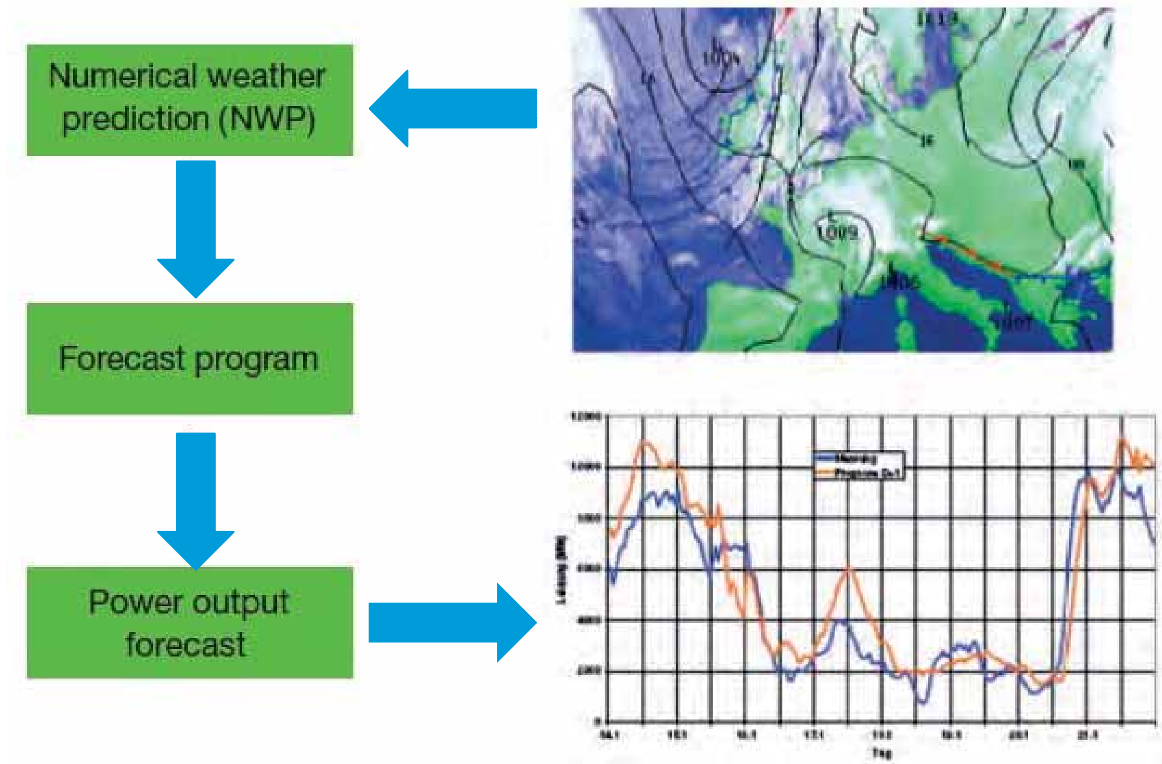
Challenges of RE generation to the grid - unpredictability

Forecasting (wind power forecasting for example)



Physical methods

Statistical methods

Challenges of RE generation to the grid - unpredictability

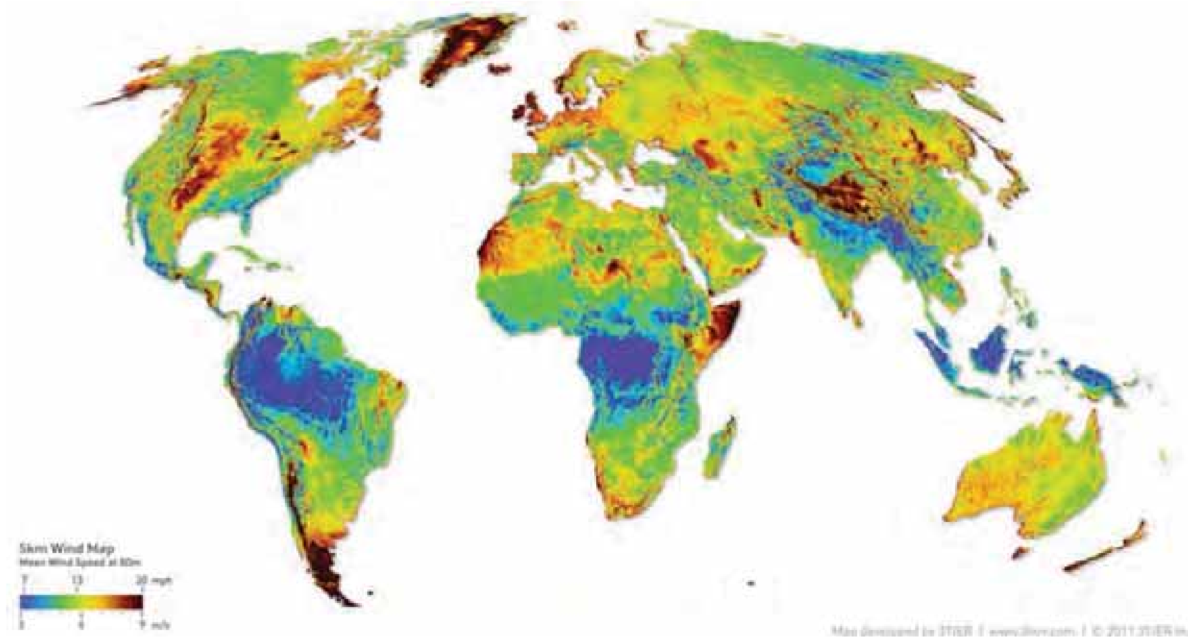
Physical methods vs. Statistical methods

Methods	Advantages	Disadvantages
Physical methods	• Require no historical power output data for the wind farms; suitable for new wind farms. • Based on detailed analysis of each atmospheric process; the forecasting model can be optimized to obtain more accurate forecasts.	• Very sensitive to systematic errors caused by incorrect initial information.
Statistical methods	• High accuracy can be achieved if high-quality data can be obtained. • Self-adjustment can be made to give appropriate output even if the input is not included in the training set.	• Require a great deal of highly consistent historical data. • Work like a black box, difficult to understand the learning and decision-making process and optimize the model.

Challenges of RE generation to the grid - location

3. Location dependence

- Because wind and solar resources are often located in remote locations, far from load center, developing sufficient transmission to move RE to markets is critical to their integration.



Global mean wind speed at 80 m altitude

- RE could be generated in one country and then transmitted and consumed in another country → long-distance transmission → challenge in control and transmission

Location dependence → expansion of transmission

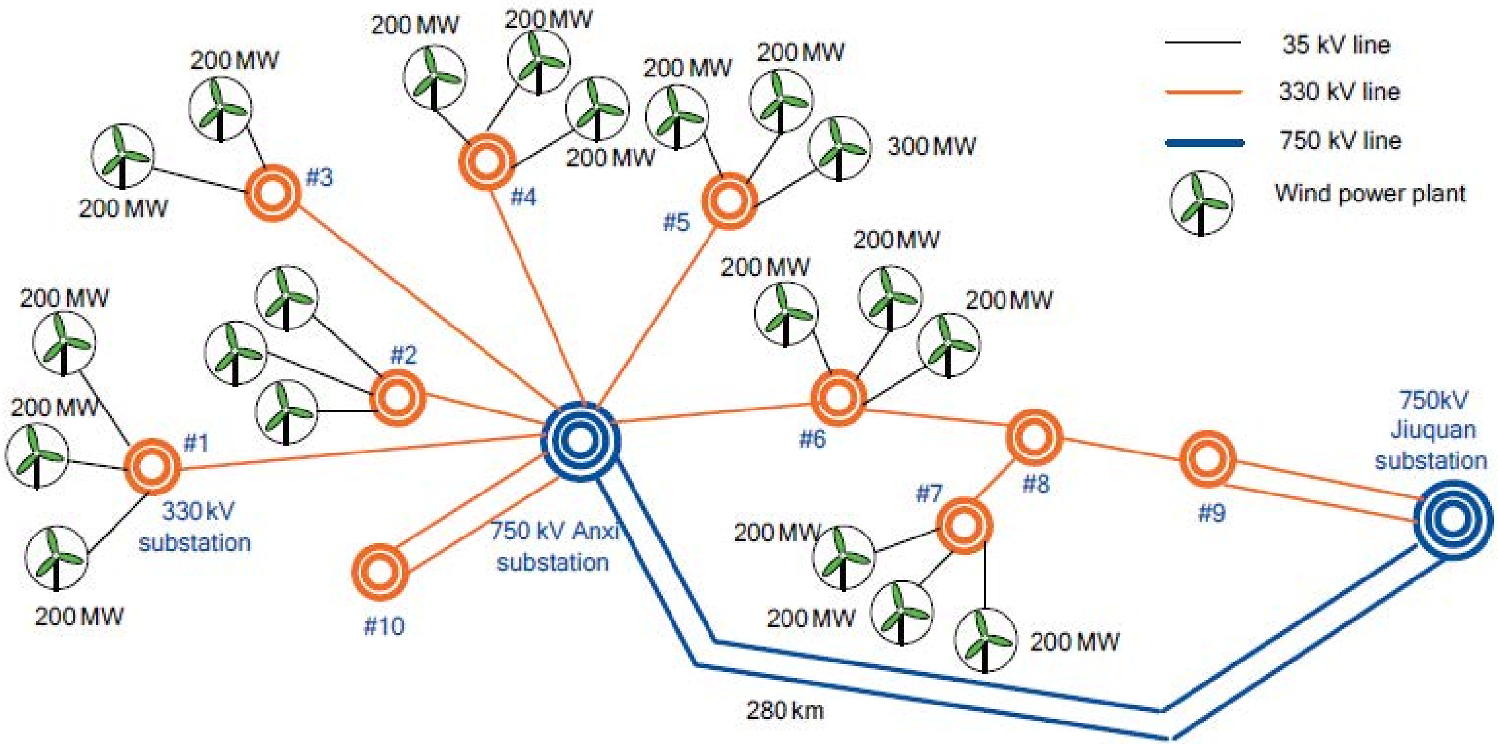
- In contrast to the convention fossil fuel power sources, selecting a site to exploit certain RE resources has few or no degrees of freedom.
- In other words, RE such as wind and solar power, are site-constrainted.
- Transmission needs to be extended to these sources, not the other way around.

- The dispersion and granularity (limited capacity) of RE sources add more challenges to transmission (planning, construction, capital cost, environmental factors…)
- For example, the 26,047 MW of total wind power developed in the US during 2006-2009 come from **546** different sites, whose average size was only 90 MW (US. DOE 2008).
- While a single Three Gorges Dam hydropower plant (China) has installed capacity of 22,500 MW.

M. Madrigal, S. Stoft, Transmission expansion for RE scale-up emerging lessons and recommendations

Challenges of RE generation to the grid - location

A centralized cluster control system, configured in a multi-layer structure, can be used to coordinate the active and reactive power control of a RE power plant cluster, just as cascaded hydro power plants on a river are controlled.



Cluster control diagram of the Gansu Wind Power, China

Challenges of RE generation to the grid - location

An example -- When HVDC line is used to transmit wind power,

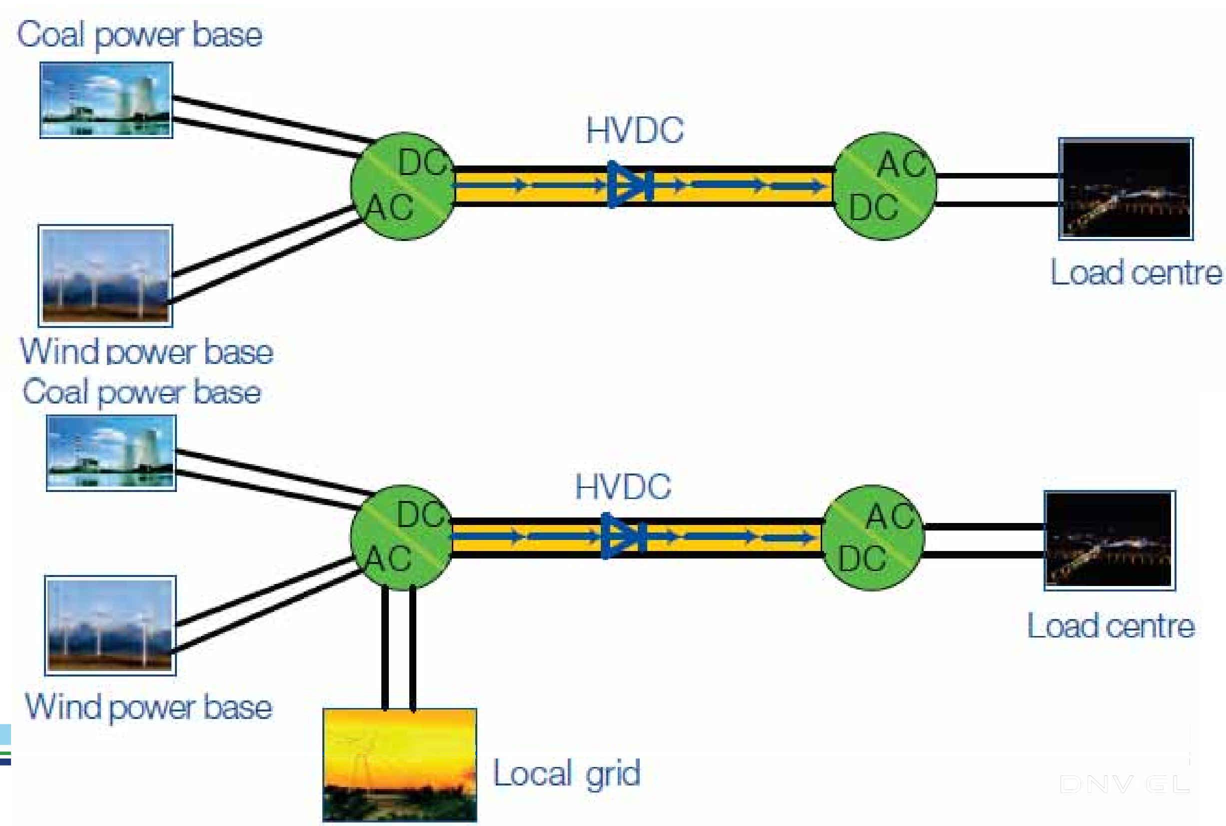
- Low utilization rate
- Minimum startup power
- Frequency stabilization

Solution #1

- Wind-fire bundling design in HVDC transmission
- Frequency problem remains

Solution #2

- Wind-fire bundling with local grid support



Challenges of RE generation to the grid – other impacts

- System protection

  Penetration of a renewable distributed generator (DG, such as PV) into an existing distribution system has other impacts on the system, e.g. to the power system protection:

  - DG causes the system to lose its radial power flow (reversed powerflow),
  - DG also changes the magnitude & radial of short circuit current.
  - These all result longer fault clearing time.

Demand Response – a good solution to ease the impact

- Demand response (DR), the development and extension of traditional demand-side management or load management practices, is recognized as a key application of the smart grid.

- The US Federal Energy Regulatory Commission's (FERC) definition of DR is:

> "Changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized"

IEC white paper *Grid integration of large capacity renewable energy sources and use of large capacity electrical energy storage*

Challenges of RE generation to the grid

Demand Response – a good solution to ease the impact

- As RE penetration rises, DR's value as an additional source of power system flexibility to compensate for the variability and uncertainty of RE generation will increase.
- DR can help RE integration in two main ways, load shifting and demand –side balancing.
- Load shifting: DR can be deployed to transfer a part of the load to off-peak periods to absorb excess RE generation, particularly for wind power generation, which often generates more power during off-peak periods and less power during peak demand periods -- reducing its capacity utilization efficiency. [Denmark]
- Demand-side balancing: Fast-acting DR can be deployed to help balance generation and load in real time. Loads can be aggregated and directed to respond very quickly and therefore be capable of following the fast ramps of RE generation, reducing the need for ramping capability from conventional generation.

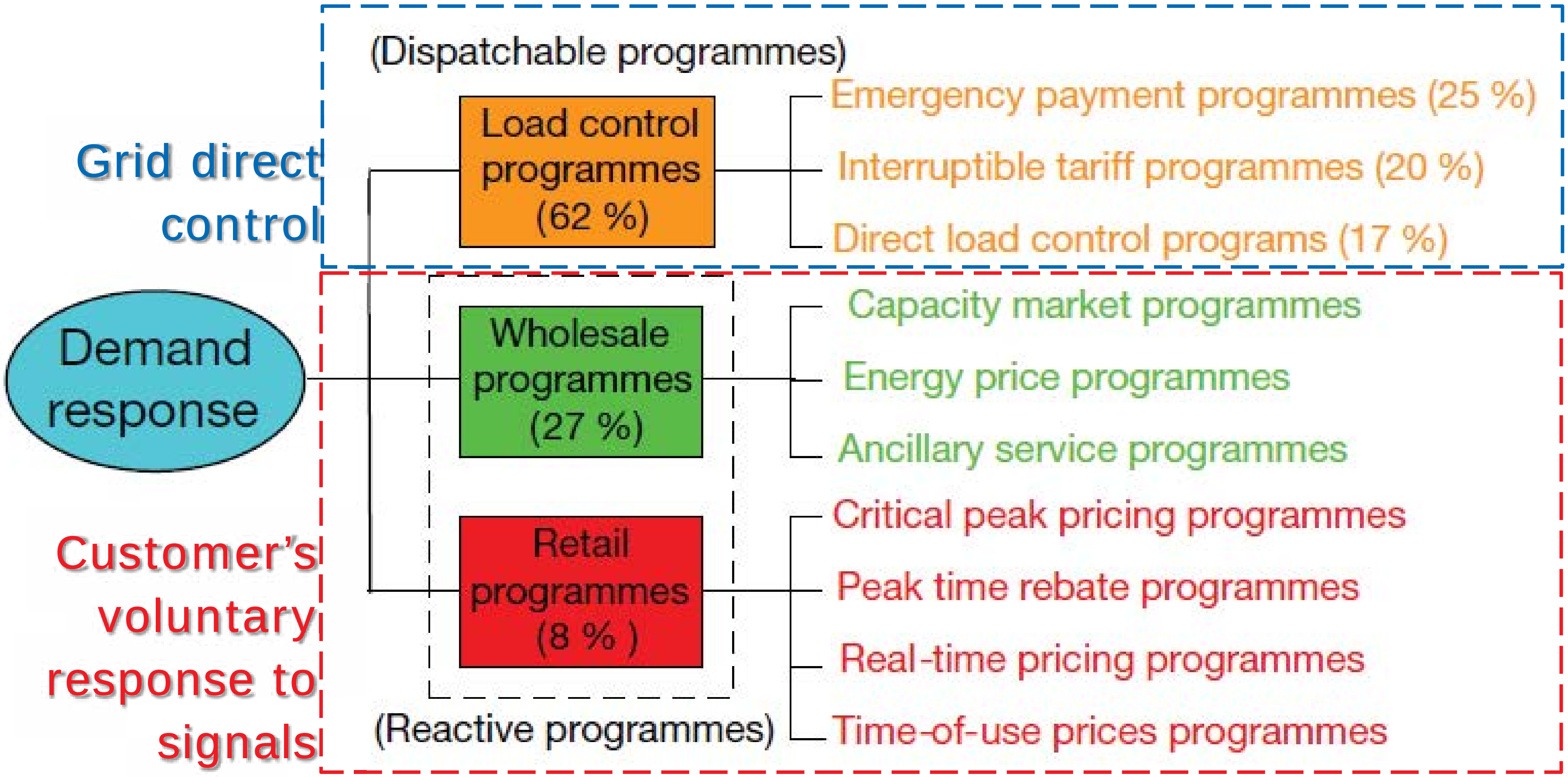
Demand Response – a good solution to ease the impact

Purpose of DR can be categorized as

- Improving system reliability
  - A customer, often a large industrial facility, agrees to reduce load to guarantee system reliability under peak demand conditions or other emergency system events, and is paid an incentive for doing so.
- Improving system efficiency
  - Many DR program have begun to focus on non-crisis peak shaving – flattening load curves to improve the efficiency of long-term power system capacity use.
- Improving system flexibility
  - Refer to demand-side balancing services

Demand Response – a good solution to ease the impact

Types of DR programs in US



Demand Response – a good solution to ease the impact

Technologies to support Demand Response

1. Advanced metering infrastructure (AMI) – Smart Metering
   – Two-way communication between customer and the utility

2. Intelligent home appliance
   – E.g. smart washing machines

3. Energy storage and electric vehicle

4. Cyber security

Challenges of RE generation to the grid
Electrical Energy Storage (EES) – another beautiful solution

- Both active and reactive power available
  - Especially, using reactive power will NOT affect battery State Of Charge

- Voltage and frequency stabilization

- Solving over- / under- voltage problems

- Correcting power factor

A real project site with EES - I used to work there

- http://www.networkrevolution.co.uk/

Northern Powergrid puts electrical energy storage to the test

Published: 27 February 2014

Six giant batteries have been installed and switched on by Northern Powergrid as part of a cutting-edge trial of electrical energy storage technology.

The devices absorb excess electricity from the network and store it for future use to make the network more efficient and help network operators respond quickly to spikes in demand for electricity.

A mixture of rural and urban locations in the Northeast and Yorkshire were selected for the devices, which are already supporting the supply of electricity to thousands of homes and businesses in the region.

The biggest of the six batteries has a capacity of 5MWh, making it one of the largest currently in operation in Europe.

Ian Lloyd, Network Technology Project Manager at Northern Powergrid, said: "This is the first time that such a comprehensive trial of energy storage technology has taken place in the UK and what makes it so unique is both the size of our largest battery and the fact that, for the first time, we are monitoring all six of the batteries through a sophisticated control system that allows us to see in real time when and where we need to release the stored energy.

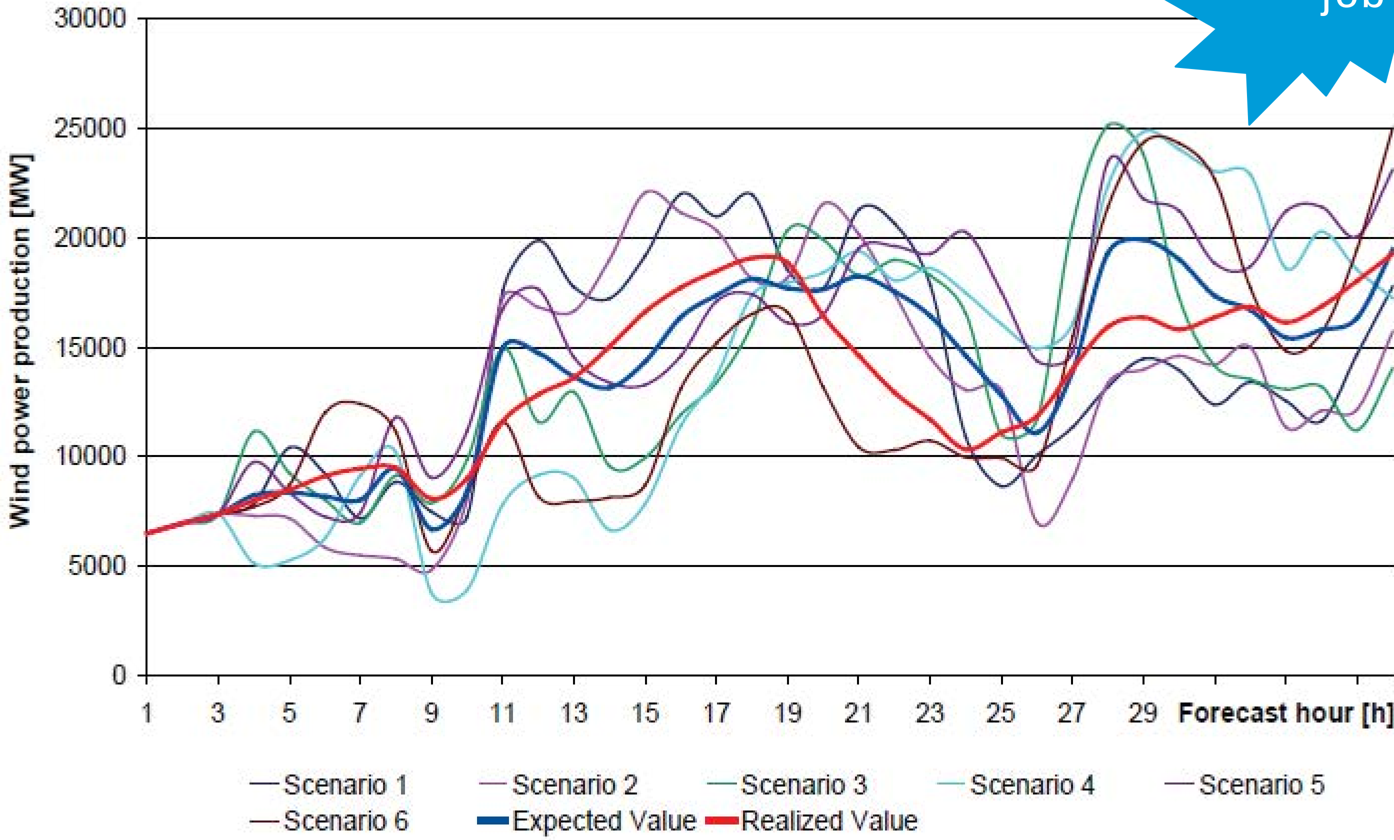
- Customer-led network revolution project (CLNR) – UK's largest smart grid project;
- Four distribution network in North East are chosen for trials of various technologies;
- Six batteries (A123) with three different sizes: 5MWh (largest, on MV), 0.2MWh and 0.1MWh (on LV)
- To solve voltage problem; to smooth out RE power
- More info: please search "CLNR" in YouTube.

Layout

- **Basics of renewable integration**
  - Wind energy
  - Solar energy
  - Transmission
- **Challenges of integrating and scaling up renewable energy**
  - Challenges & barriers of increasing the penetration of renewable energy
  - Overview of solutions
- **Importance of renewable energy forecasting in grid operation**
- **Q&A**

RE power forecasting

Tough job

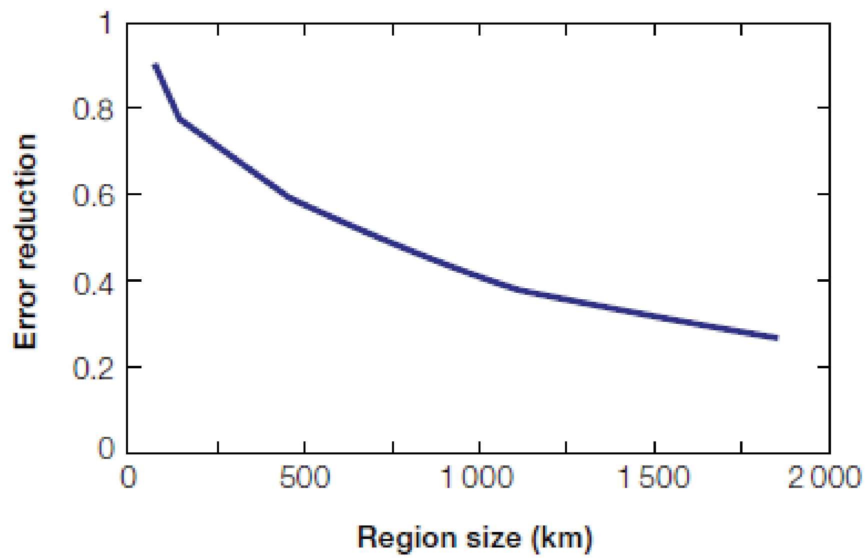


Example of a day-ahead forecast scenario tree for the wind power forecast for the PJM region of the United States

RE power forecasting

Forecast accuracy

- Spatial aggregation greatly reduces forecast errors, just as it reduces variability.
- This is due to spatial smoothing effects.
- Below shows a case of 40 wind farms in Germany: aggregation over a 750 km region may reduce forecasting error by about 50%.

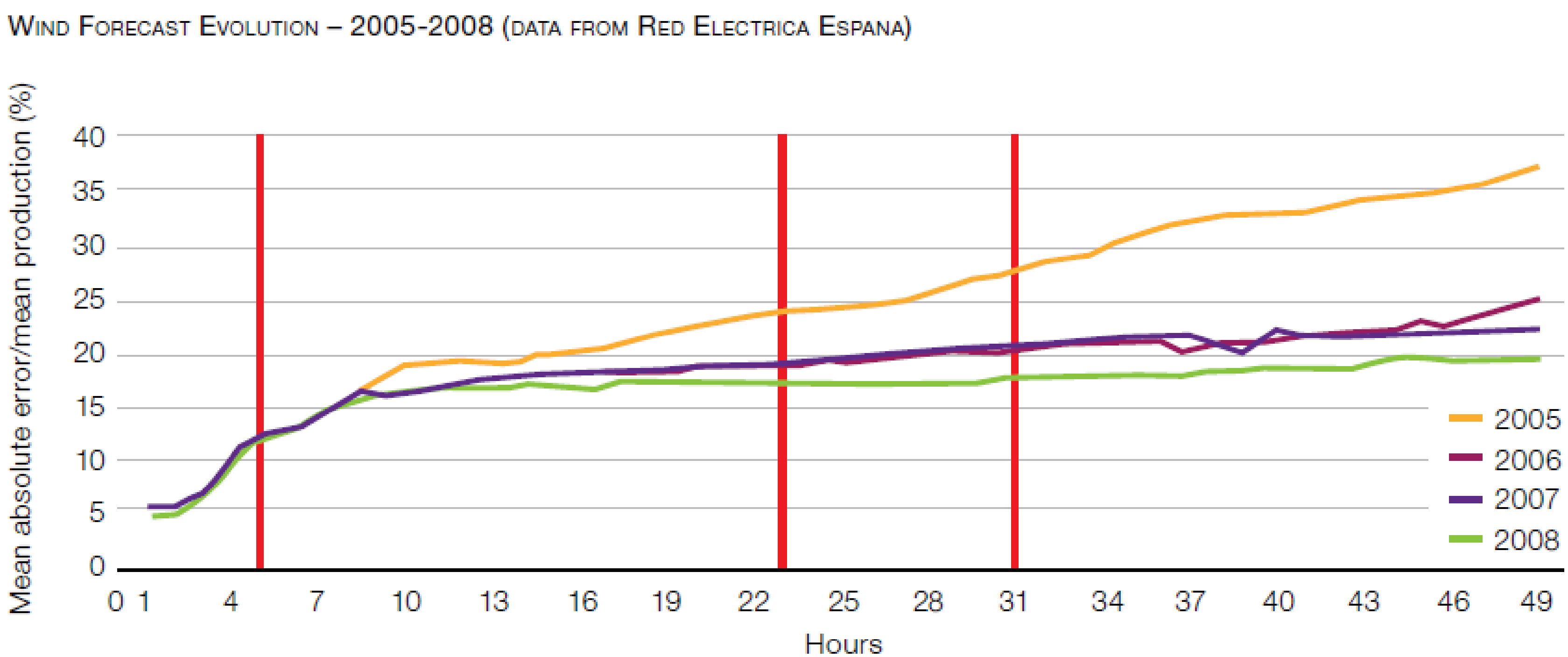


Decrease of wind forecast error for aggregated wind power production [case in Germany]

RE power forecasting

Forecast accuracy

- The forecast error increases as the time horizon of the forecast increases
- Forecasting techniques are improving constantly.



Wind forecast error as a percentage of wind production, as a function of the time forward from the present

RE power forecasting

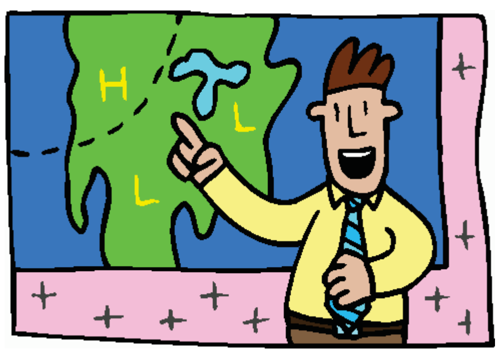
Forecast accuracy – how to improve it

1. Model and data improvement
   - Better weather model; better data collection and processing

2. Centralised forecast & ensemble forecast
   - Spatial smooth effect

3. High-resolution plant level & nodal injection forecast

4. Ramp event forecast (severe weather events)



5. Human behaviour forecast

6. Probabilistic forecast

Case study: benefits of accurate RE forecasting

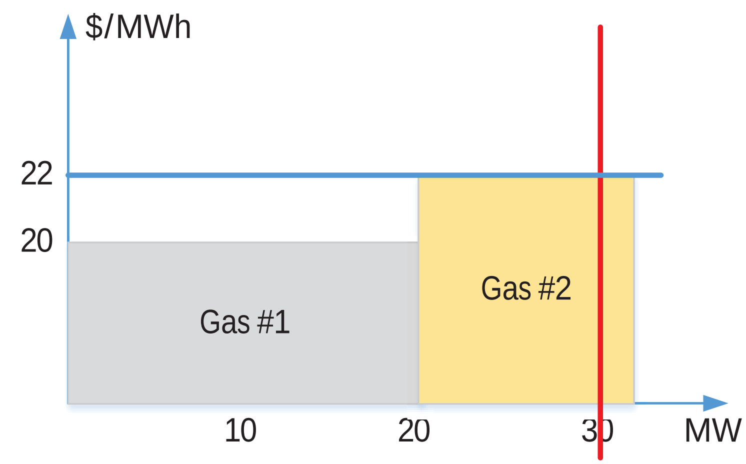
- Day-ahead market clearance pricing scheme;
- Forecasting peak load of 30MW for 4 hours;
- Gas turbine plant #1 (Gas #1): capacity 20MW, biding price $20/MWh, cost $18/MWh;
- Gas turbine plant #2 (Gas #2): capacity 20MW, biding price $22/MWh, cost $19/MWh;
- Wind farm capacity 15MW

Case study: benefits of accurate RE forecasting (cont.)

- Day-ahead market clearance pricing scheme;
- Forecasting peak load of 30MW for 4 hours;
- Gas turbine plant #1 (Gas #1): capacity 20MW, biding price $20/MWh, cost $18/MWh;
- Gas turbine plant #2 (Gas #2): capacity 20MW, biding price $22/MWh, cost $19/MWh;
- Wind farm capacity 15MW

Case #1: load 30MW for 4 hours. Only Gas #1 and #2 to bid market price. No Wind.

Customer paid price:	$22/MWh
Customer paid amount:	22*30*4= **$2,640.00**



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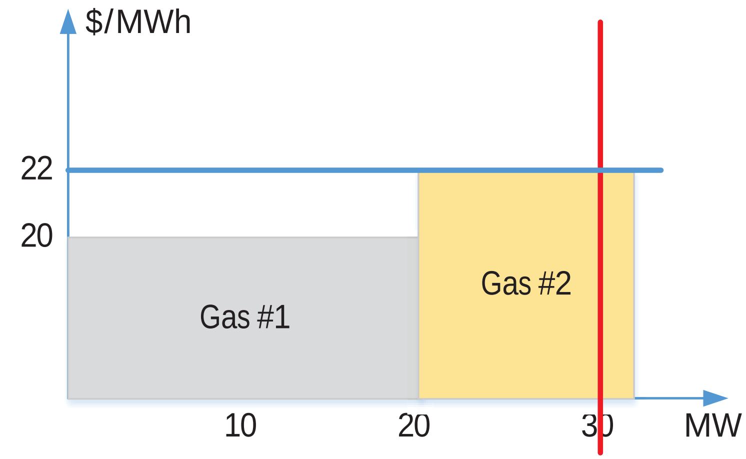
Case study: benefits of accurate RE forecasting (cont.)

- Day-ahead market clearance pricing scheme;
- Forecasting peak load of 30MW for 4 hours;
- Gas turbine plant #1 (Gas #1): capacity 20MW, biding price $20/MWh, cost $18/MWh;
- Gas turbine plant #2 (Gas #2): capacity 20MW, biding price $22/MWh, cost $19/MWh;
- Wind farm capacity 15MW

Case #2: load 30MW for 4 hours. Wind did not bid but generated 10MW for 4 hours. So Gas #2 was commanded to reduce output.

Customer paid price:	$22/MWh
Customer paid amount:	22*30*4= **$2,640.00**
Wind revenue:	22*10*4= **$880.00**
Wind penalized:	(22-19)*10*4= **$120.00**

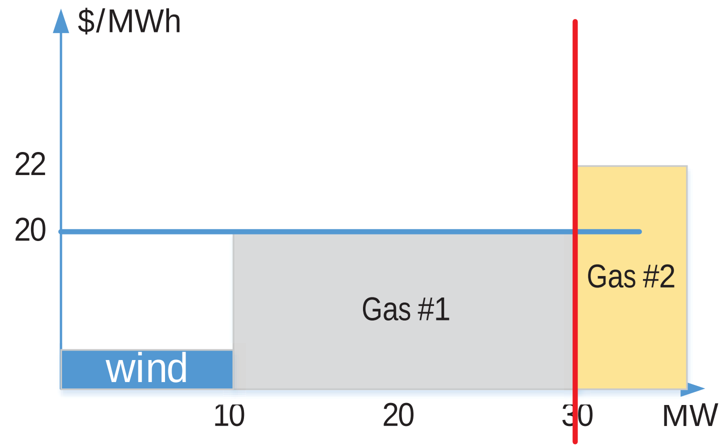


Case study: benefits of accurate RE forecasting (cont.)

- Day-ahead market clearance pricing scheme;
- Forecasting peak load of 30MW for 4 hours;
- Gas turbine plant #1 (Gas #1): capacity 20MW, biding price $20/MWh, cost $18/MWh;
- Gas turbine plant #2 (Gas #2): capacity 20MW, biding price $22/MWh, cost $19/MWh;
- Wind farm capacity 15MW

Case #3: load 30MW for 4 hours. Wind generated 10MW for 4 hours as it was forecasted. So market price reduced

Customer paid price:	$20/MWh
Customer paid amount:	20*30*4= **$2,400.00**
Wind revenue:	20*10*4= **$800.00**
Wind penalized:	0

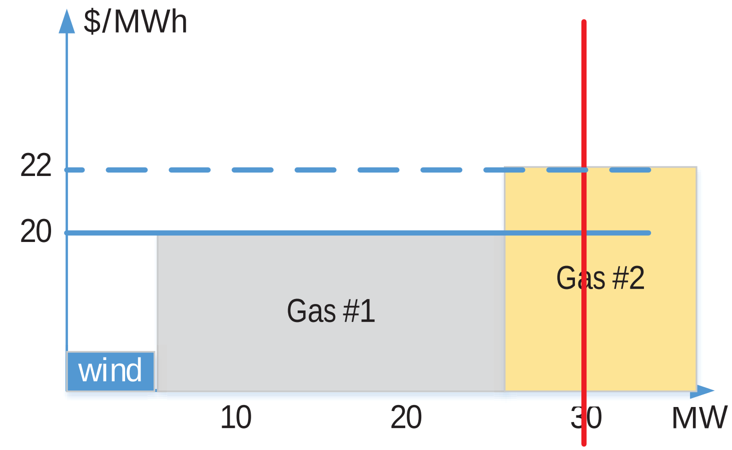


Case study: benefits of accurate RE forecasting (cont.)

- Day-ahead market clearance pricing scheme;
- Forecasting peak load of 30MW for 4 hours;
- Gas turbine plant #1 (Gas #1): capacity 20MW, biding price $20/MWh, cost $18/MWh;
- Gas turbine plant #2 (Gas #2): capacity 20MW, biding price $22/MWh, cost $19/MWh;
- Wind farm capacity 15MW

Case #4: load 30MW for 4 hours. Wind was forecasted 10MW but only managed to generate 5MW. So Gas #2 had to re-dispatch.

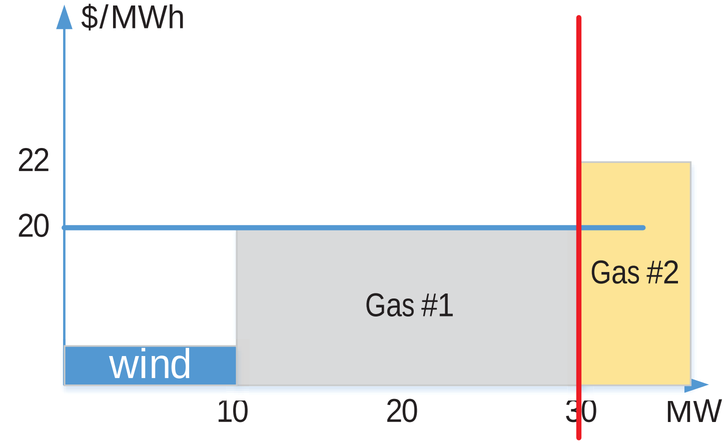
Customer paid price:	$20/MWh
Customer paid amount:	20*30*4= **$2,400.00**
Wind revenue:	20*5*4= **$400.00**
Wind penalized:	(22-20)*5*4 **$40**



Case study: importance of accurate RE forecasting (cont.)

- Apparently Case #3 is the best case, in which the public had cheaper electricity price while wind industry had better profit.

Customer paid price:	$20/MWh
Customer paid amount:	20*30*4= **$2,400.00**
Wind revenue:	20*10*4= **$800.00**
Wind penalized:	0



Summary

- Basics of RE sources (wind and solar)
- Challenges of integrating RE sources to the grid & the solutions
  - Uncontrollable variability
  - Unpredictability
  - Location dependence
- Challenges of scaling up RE to transmission
  - Solutions like Demand Response
- RE power forecasting – importance & benefits

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